FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 7 No. 5, October, 2023, pp 296 - 317
DOI: https://doi.org/10.33003/fjs-2023-0705-2025

SEDIMENTOLOGICAL ANALYSIS, DEPOSITIONAL ENVIRONMENT AND SEQUENCE STRATIGRAPHIC STUDY OF IDA 4, 5, 6 WELLS NIGER DELTA BASIN, NIGERIA

Jacinta Nkiru Chukwuma-Orji

Department of Geology, Federal University of Technology Minna, Niger State, Nigeria

*Corresponding authors' email: jacinta@futminna.edu.ng
ORCID ID: 0000-0001-9541-2566

ABSTRACT

Sequence stratigraphic study divides sedimentary successions into unconformity or maximum flooding surface bounded units (sequence) that form during a single, major cycle of sea-level change. Detailed sedimentological and sequence stratigraphic studies of the strata penetrated by Ida-4, 5, and 6 wells were carried out to deduce the depositional environment and correlate the stratigraphic units. The wells are located in the coastal swamp depobelt of the Eastern Niger Delta. Studied samples were dry-sieved for sedimentological analyses. Each fraction was studied under reflected light microscope. The lithology consists of an alternation of shale and sandstone units. The grain size of the sandstone units consists of fine to medium grains, occasionally coarse to granule-sized grains. Dominant accessories minerals are ferruginous materials, shell fragments, carbonaceous detritus, and few records, of mica flakes, glauconite, and pyrite. Regular sand and shale intercalation pattern on the Gamma Ray log permitted easy recognition of sub-cycles (autocycles) of sedimentation in an extensively developed paralic sequence. Paleoenvironmental reconstruction using accessories minerals recognizes shallow water settings with intermittent deeper water conditions. Rapid sedimentation rates are inferred in the studied area based on the observed alternation of thick sandstone, shale, and mudstone units. The MFS and SB were dated 9.5 Ma and 10.35 Ma respectively. Lithologic and system tracts correlations show lateral continuity of sandstone units (potential reservoirs) depicted in the lithofacies subcycles correlation. This is useful in the determination of reservoir geometry, areal coverage, and calculation of the volume of accumulated hydrocarbon, and directing well trajectory during the drilling operation.

Keywords: Sedimentary successions, autocyclic sedimentation, paleoenvironment, lithofacies correlation, system tracts

INTRODUCTION

The Ida Field is located within the onshore area of the Niger Delta (Fig. 1). Ida-4 is located at latitude 4.82° N and longitude 6.86° E; Ida-5 is located at latitudes 4.80° N and longitude 6.76° E; Ida-6 well is located at latitude 4.73° N and longitude 6.96° E in the coastal swamp depobelt of the Eastern Niger Delta Nigeria (Fig. 1). Niger Delta lies between latitudes 4° and 6° N and longitudes 3° and 9° E respectively in the southern part of Nigeria (Fig. 1).

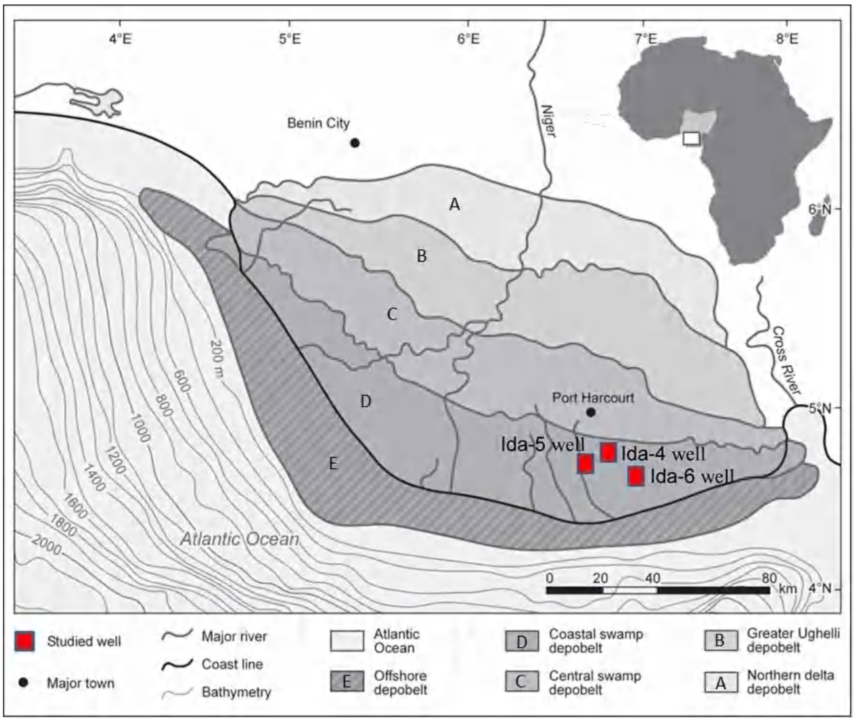

Figure 1: Depobelt of the Niger Delta Basin and location of the studied wells (modified after Chukwuma-Orji et al. 2019).

Boggs (2006) and Reijers (2011) stated that in cyclic lithofacies successions, Authocyclic and Allocyclic are recognized based on the processes that form them. Authocyclic successions are caused by local sedimentary processes (natural redistribution of energy) that take place within the basin itself, such as switching delta lobe due to repeated progradation and retreat, channel meandering, and delta avulsion. Their resultant beds show limited stratigraphic continuity (Boggs 2006; Reijers 2011). Allocyclic successions are controlled by variations in mechanisms that are external to the basin such as climatic changes, tectonic movements (subsidence), and global (eustatic) sea-level fluctuations (Boggs 2006). These result in regional and delta-wide sediment distribution patterns. Both cycles have been identified in the Niger Delta (Reijers 2011). Authocyclic cycles are superimposed on the allocyclic ones with the resultant sequences depicting local and delta-wide sedimentary processes (Fig. 2). According to Reijer (2011), the interference of autocycles and allocycles results in delta-wide genetic sequences (mega sequences) defined by Vail (1987) and Galloway (1989). Vail (1987) defined depositional sequence as genetically related strata bounded by unconformities or their lateral equivalent, while Galloway (1989) defined it as genetically related strata bounded by maximum flooding surfaces. The delta-wide genetic sequences (mega sequences) are sedimentologically characterised and chronostratigraphically confined. The focus of this work is to combine existing palynofacies data, Gamma Ray Logs, sedimentological data and seismic profile to determine the paleoenvironment of deposition, system tracts and correlation of the studied intervals.

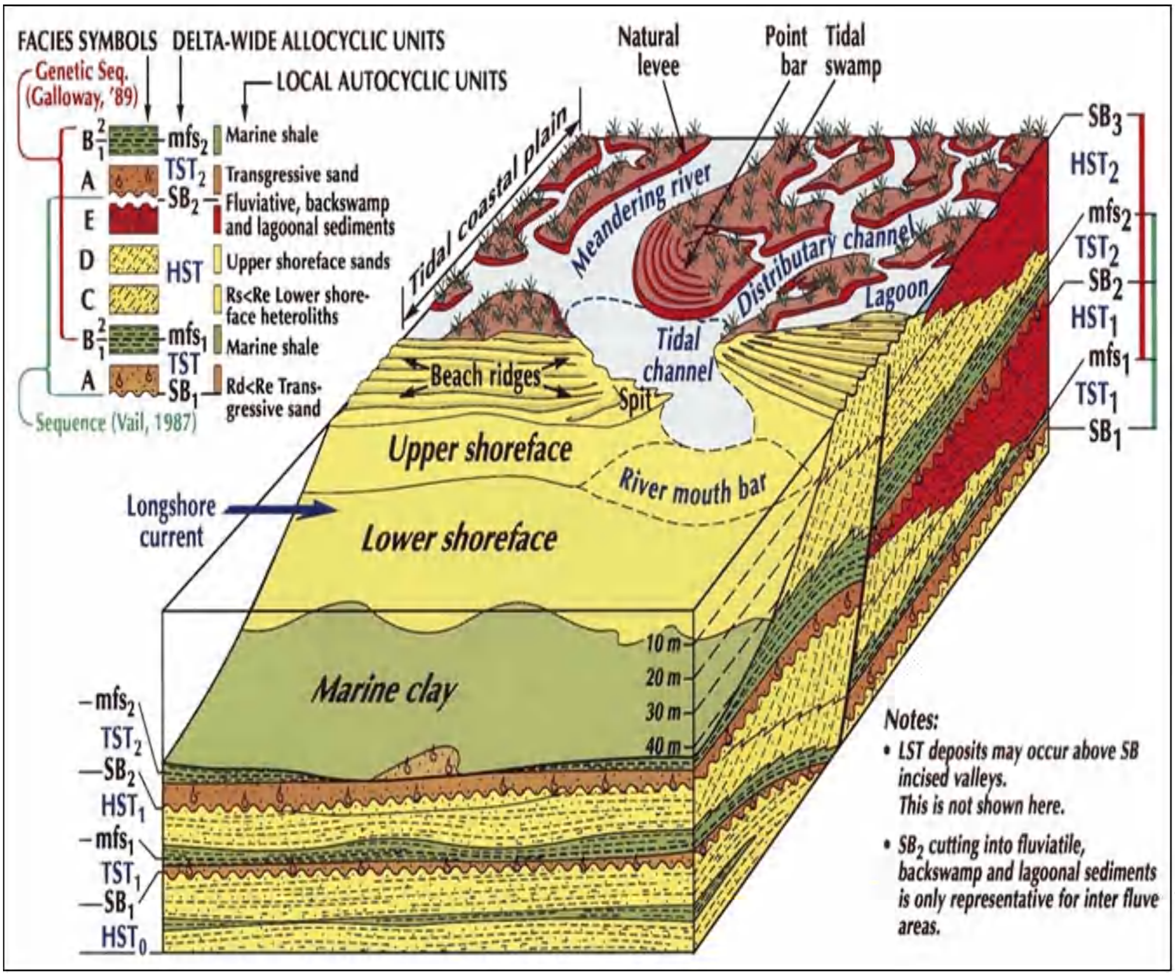

Figure 2: Geomorphology, cyclic sedimentation, and active fault in the coastal zone of the Niger Delta (Reijers 2011)

Geology of the study area

The geology of the Niger Delta Basin comprises three formations (Figure 3). Stratigraphically from oldest to youngest, these are the Akata Formation (Age: Paleocene – Recent), Agbada Formation (Age: Eocene – Recent), and Benin Formation (Age: Oligocene – Recent). The stratigraphic succession generally displays a coarsening-upward trend more than 12 km thick. The Akata Formation is characterized by shales, clays, and minor sandstone intercalations which were deposited in prodelta environments. The percentage of sandstone in this formation is less than 30% (Obaje, 2009). The Agbada Formation was deposited in a transitional environment (lower delta plain). It comprises alternating sandstone and shale units. The percentage of sandstone in the Agbada Formation varies from 30 to 70%. The Benin Formation is continental to upper delta plain deposits comprising sandstone, thin shales, coals, and gravels. The percentage of sandstone is also variable (70–100%) (Obaje, 2009). Doust & Omatsola (1990) recognised that depobelts in the Niger Delta are distinguished principally by their age and location. These are the Northern Delta, Greater Ughelli, Central Swamp, Coastal Swamp, and Offshore depobelts (Fig. 1). Short & Stauble (1967), in the description of the stratigraphy of the Niger Delta, recognized three formations.

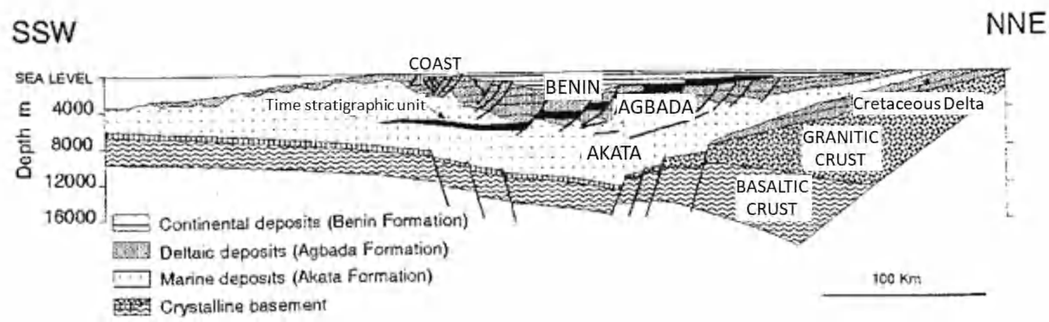

Figure 3: Stratigraphic succession of the Niger Delta (Obaje, 2009).

MATERIALS AND METHODS

Methods of Study

Fifty ditch cuttings each from Ida-4 (interval: 2152 – 3523 m), Ida-5 (intervals: 2207 – 3569 m), and Ida-6 (interval: 2679 – 4051 m) were studied. Sample availability was a limiting factor to the intervals studied in each well.

The lithologic description was done by visual examination of the samples aided by the chart for textural analysis of clastic sediments (Hallsworth & Knox, 1999), the study of the log motifs (Gamma Ray and Resistivity logs), and microscopic study of samples. The Gamma Ray Log patterns (fining and coarsening upward signatures) described by Sneider et al. (1978) and Beka & Oti (1995) were adopted (Figures. 4 and 5). The lithologic description was enhanced by the Gamma Ray and Deep Induction Resistivity Logs since high and low values of Gamma-Ray Log and Deep Induction Resistivity Log signify shale and sandstone lithologies, respectively (Adegoke 2002; Olayiwola & Bamford 2016).

Twenty grams of the samples were disaggregated and dry-sieved using 6 sets of sieves (10, 18, 35, 60, 120, 230 sieve mesh seizes and pan). Fractions retained were viewed using the standard binocular reflected light microscope (Fisher Scientific, No. 62416). The important parameters studied are: (i) the rock types; (ii) colour and texture (grain size, grain sorting, grain shape and sphericity); and (iii) accessory mineral composition and shell fragments. The lithological data were plotted using Stratabug software, to generate the vertical lithofacies profiles encountered within the studied intervals.

The sequence stratigraphic analysis involved the integration of biostratigraphic data (palynomorph and palynomaceral) with well log signatures (Gamma Ray Logs) and ditch cutting samples. The interpretation procedures of Vail and Wornardt (1991) were employed for the study.

Age and palynofacies information of the studied intervals, used in this study were obtained from the palynofacies studies of the Ida-4, 5 and 6 wells (Chukwuma-Orji et al., 2017a & b; 2019).

RESULTS AND DISCUSSION

Results

The results of the visual petrologic analyses of the cuttings from Ida-4, 5 and 6 are presented in figures 6, 7 and 8. The lithology consists of alternating shale, mudstone and sandstone with few intercalations of siltstone and sandy shale units. The shale and mudstones are mostly grey to brownish grey in colour, moderately hard to hard, platy to flaggy in appearance. The sandstones are predominantly milky white, fine to coarse-grained, angular to sub-angular to rounded, and poorly to well-sorted in texture. The accessories include glauconite pellets, shell fragments, ferruginous materials, pyrites, mica flakes and carbonaceous detritus (Figure 9). The log pattern results suggest the progradation and retrogradation of clastic sediments. The age of the studied intervals in the three wells has been dated as middle Miocene to late Miocene based on the stratigraphic age range of the recovered diagnostic marker species (Chukwuma-Orji et al., 2017a & b; 2019). The recovery of the following palynomorphs; *Crassoretitriletes vanraadshooveni, Verrutricolporites rotundiporus, Belskipollis elegans, Retibrevitricolporites protudens, Racemonocolpites hians, Zonocostites ramonae, Retistephanocolpites gracilis, Cyperaceaepollis* sp, *Multiareolites formosus* and *Nummulipollis neogericus* at different intervals in the three wells indicate that the stratigraphic intervals studied were deposited during Middle to Late Miocene (Chukwuma-Orji et al., 2017a & b; 2019).

These allowed the assignment of the entire studied intervals of Ida-4, 5 and 6 wells to the Agbada Formation. The Agbada Formation has been described as paralic (Cyclic) lithofacies sequence of marine and fluvial deposits consisting of alternation of sand/sandstone shale/mudstone units (Weber 1971; Bankole et al. 2014).

Discussion

The integration of lithology, texture, distribution of accessory materials, and Gamma-Ray Log motifs enabled the delineation of one broad paralic (Cyclic) lithofacies succession within the studied intervals (Selley 1978; Durugbo & Uzodimma 2013). The paralic lithofacies succession was subdivided further into an upper and lower Agbada paralic units based on the shale to sand ratio Durugbo & Uzodimma (2013).

The observed upper and lower paralic units were subdivided into subcycles. The subcycles were delineated using the Gamma Ray Log stacking patterns and are inferred to reflect authocyclicity in the successions (Figure 2) (Boggs 2006; Reijers 2011).

The paralic succession of Ida-4 Well (3521.96 – 2197.61 m)

This studied interval consists essentially of heterogeneous units of alternating shale, mudstone and sandstone units. The regular pattern of shale, mudstone and sandstone intercalations allowed easy delineation (on logs) of eight sub-cycles (authocyles) of sedimentation within the paralic succession. Each of these sub-cycles commences with relatively thick prodelta shale and progressively shallows into fluviatile sands. The recognised subcycles are summarised in Figure 6. The paralic succession has been subdivided into two major lithofacies units based on Gamma Ray Log patterns (fining up and coarsening up, Figures 4 and 5) and shale to sand ratio (Selley 1978; Durugbo & Uzodimma 2013); these are: -

i. The lower paralic unit (3521.96 – 3087.62 m) 434.34 m thick, and
ii. The upper paralic unit (3087.62 – 2197.61 m) 890.01 m thick.

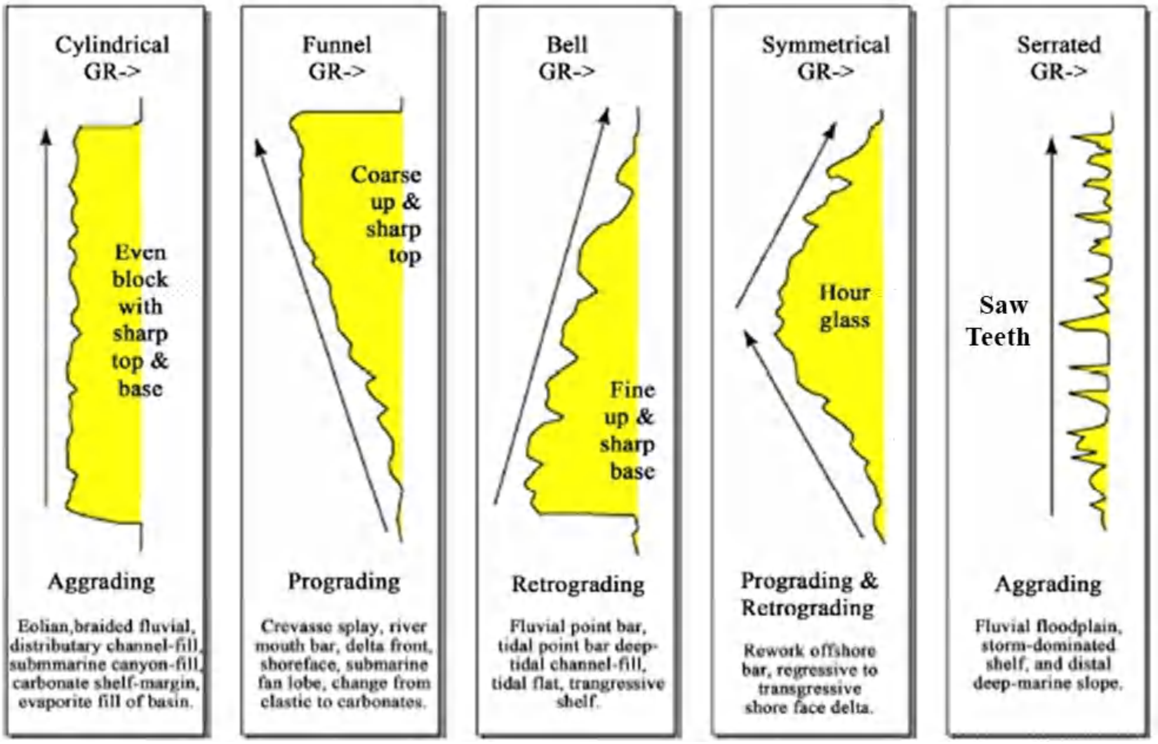

Figure 4: Different well log motifs (signatures) for different environments (Beka & Oti 1995; Onyekuru et al. 2012)

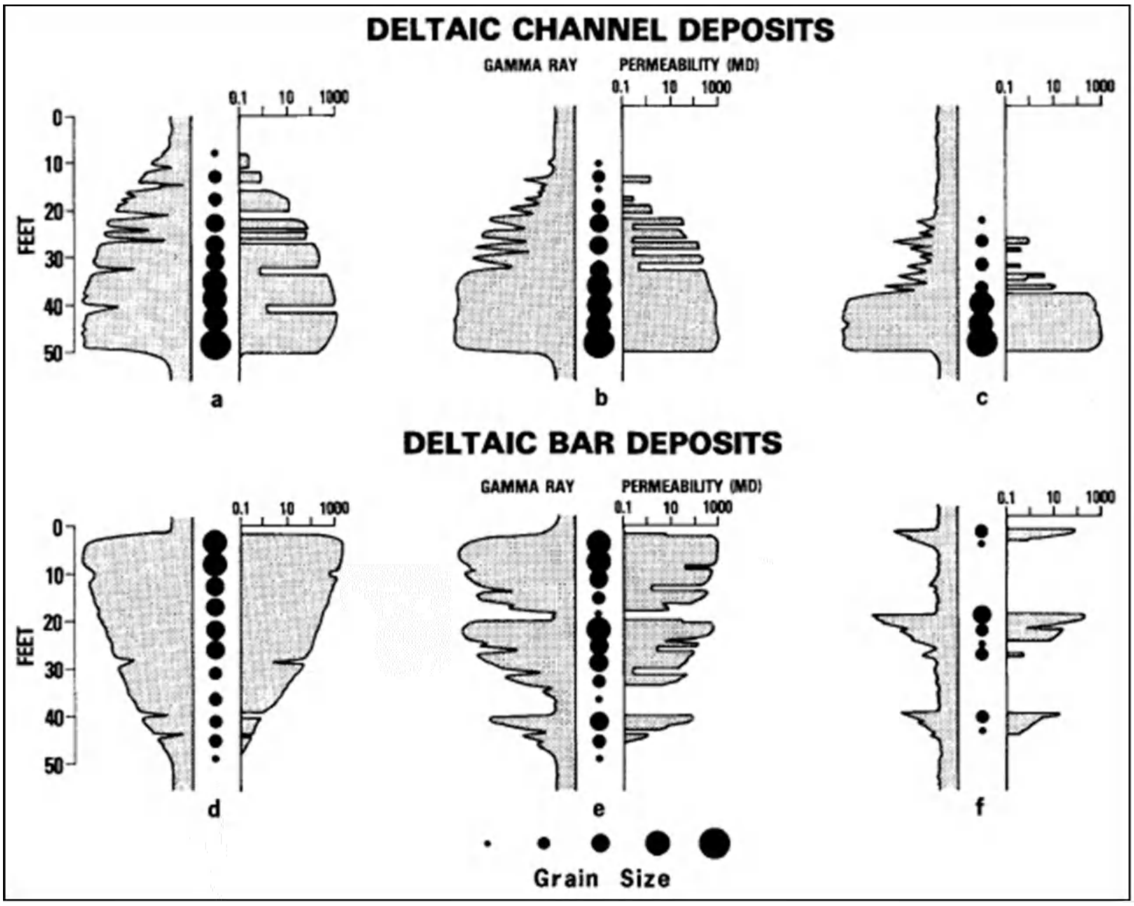

Figure 5: Idealised log responses and permeability profiles of deltaic deposits (Sneider et al. 1978)

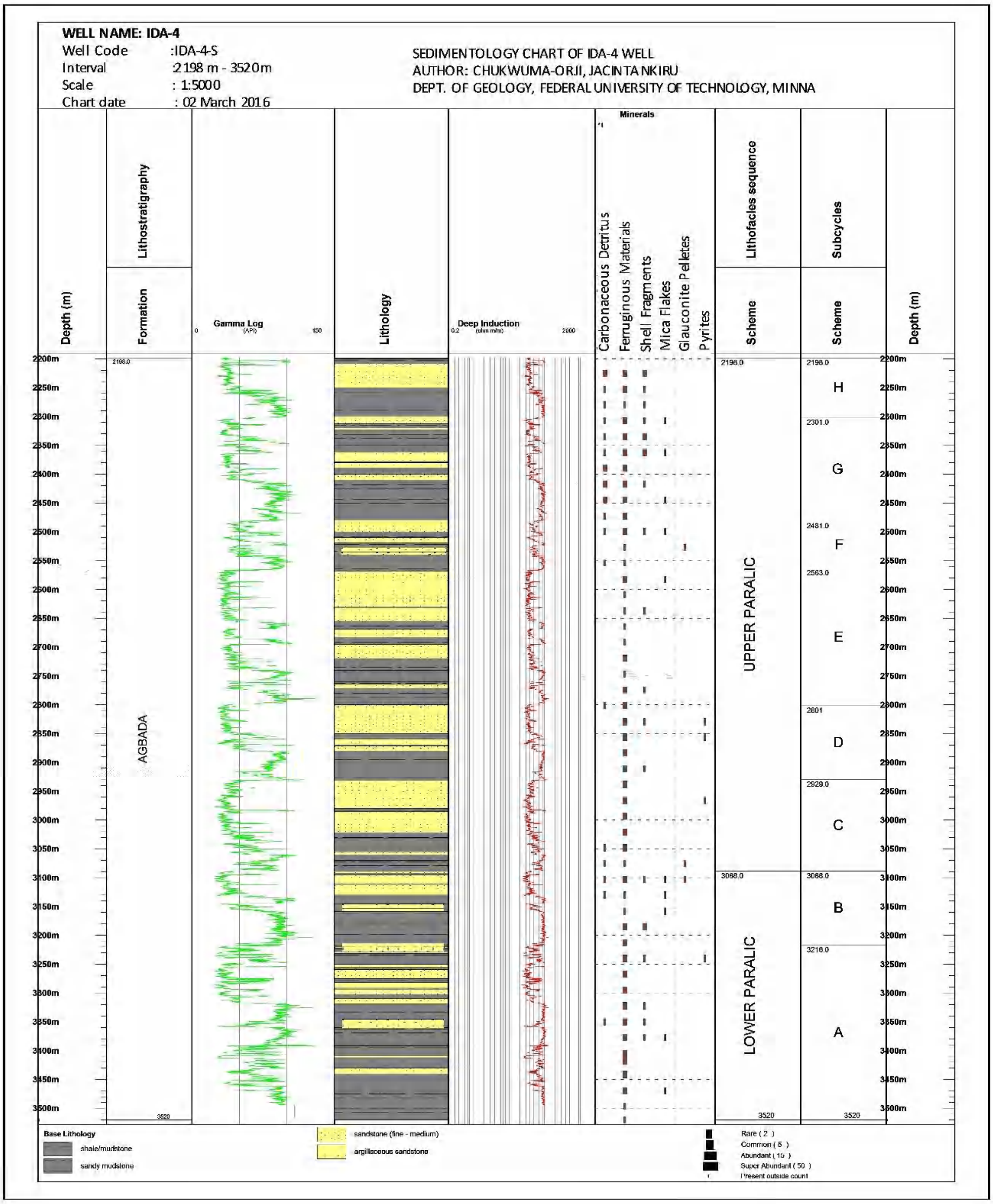

Figure 6: Lithological and sedimentological chart of Ida-4 well, onshore Eastern Niger Delta

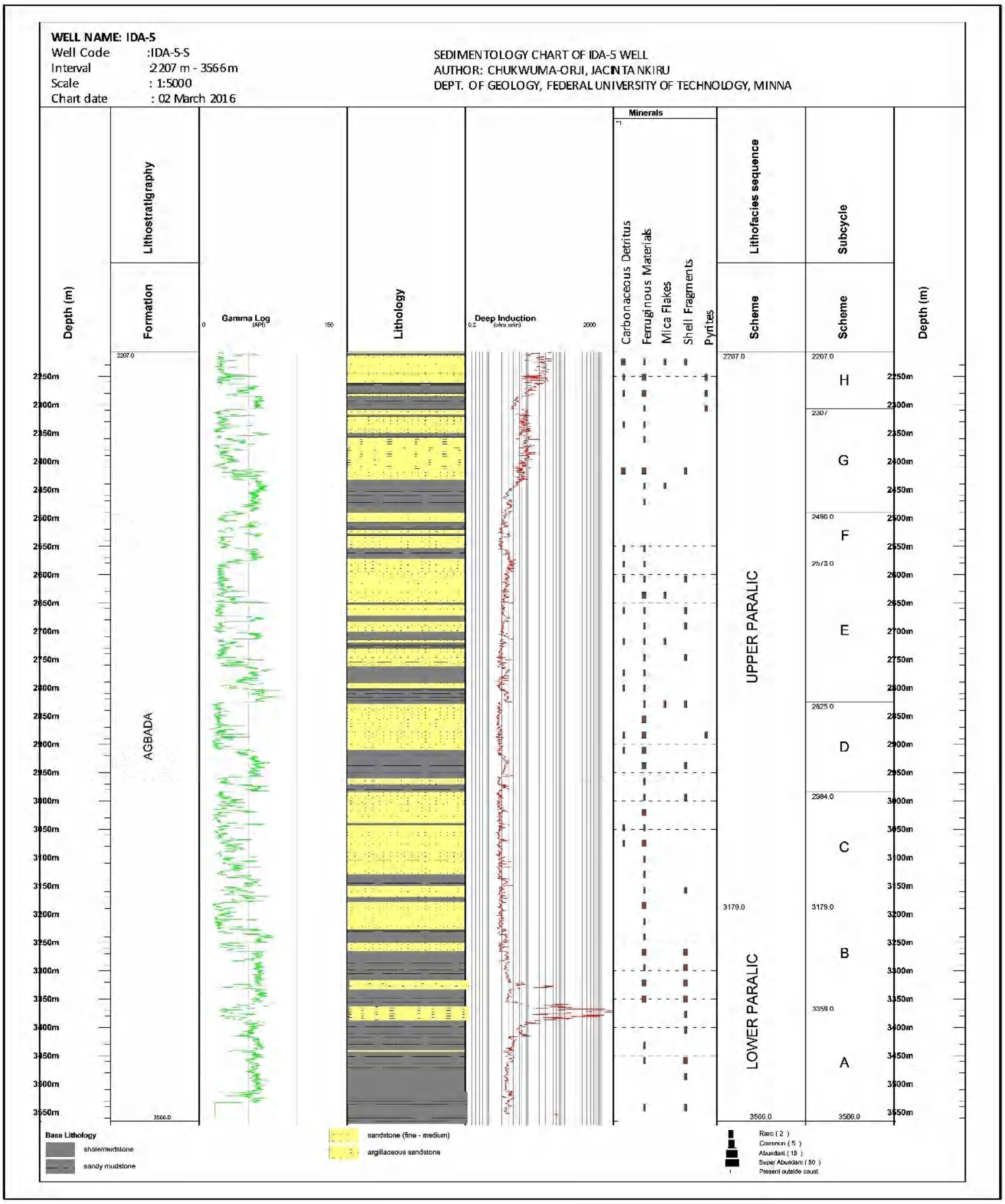

Figure 7: Lithological and sedimentological chart of Ida-5 well, onshore Eastern Niger Delta

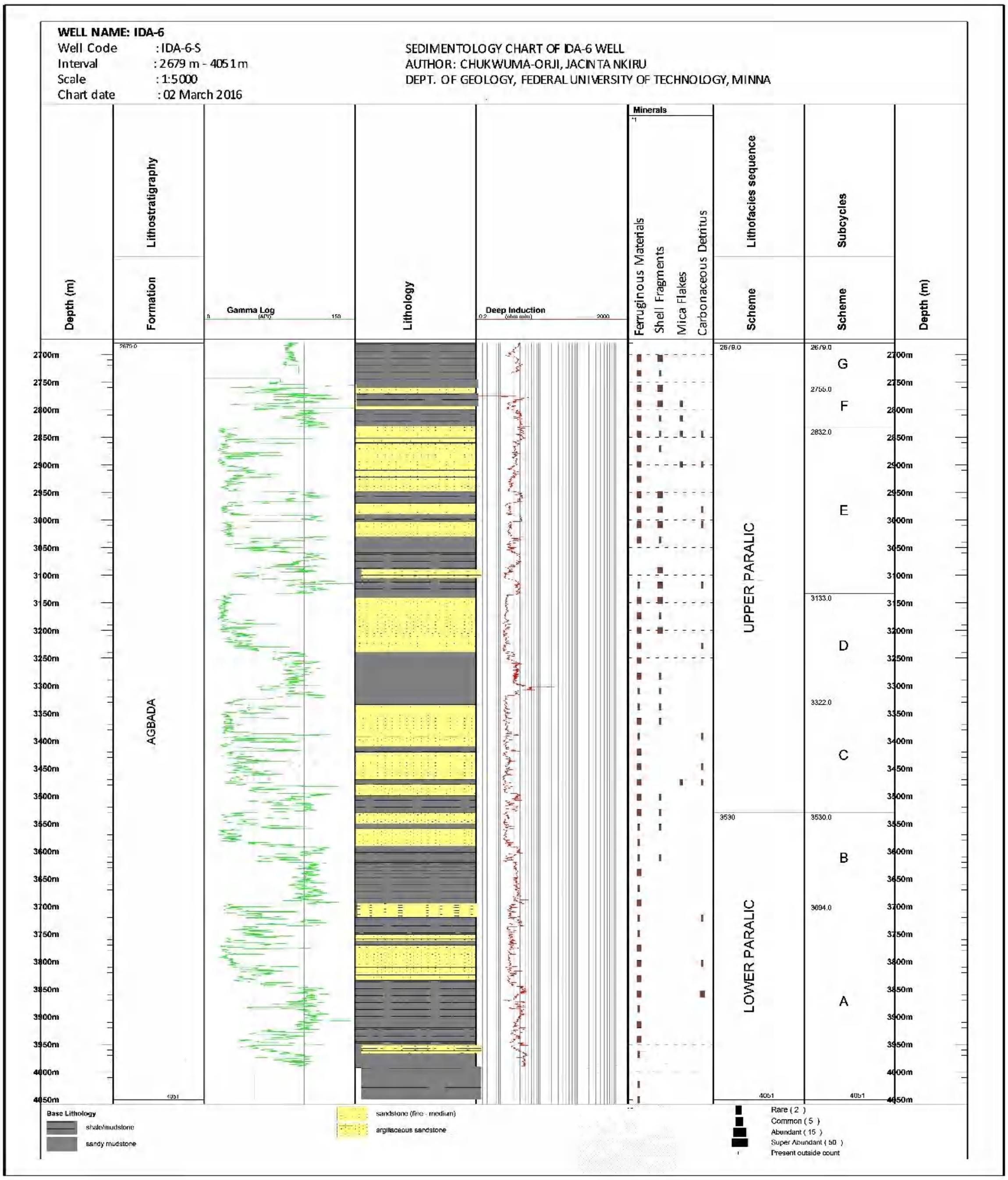
WELL NAME: IDA-6
Well Code : IDA-6-S
Interval : 2679 m - 4051 m
Scale : 1:5000
Chart date : 02 March 2016
SEDIMENTOLOGY CHART OF IDA-6 WELL
AUTHOR: CHUKWUMA-ORJI, JACINTA NKIRU
DEPT. OF GEOLOGY, FEDERAL UNIVERSITY OF TECHNOLOGY, MINNA
Depth (m)
Lithostratigraphy
Formation
Gamma Log
Lithology
Deep Induction
Minerals
Ferruginous Materials
Shell Fragments
Mica Flakes
Carbonaceous Detritus
Lithofacies sequence
Scheme
Subcycles
Scheme
AGBADA
UPPER PARALIC
LOWER PARALIC
G
F
E
D
C
B
A
Base Lithology
shale/mudstone
sandy mudstone
sandstone (fine - medium)
argillaceous sandstone
Rare (2)
Common (5)
Abundant (15)
Super Abundant (50)
Present outside count

Figure 8: Lithological and sedimentological chart of Ida 6 well, onshore Eastern Niger Delta

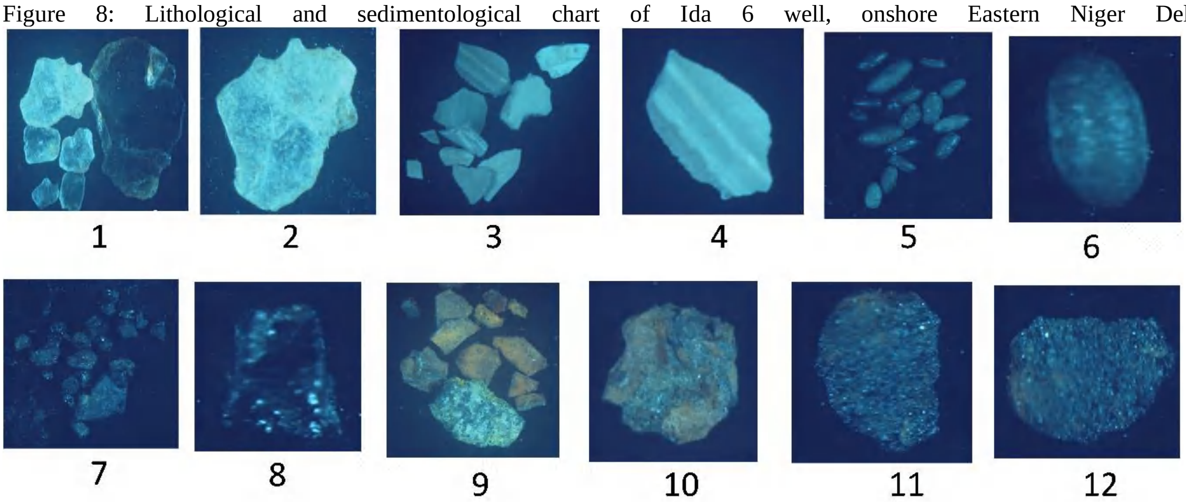

Figure 9: Some photomicrographs of the accessory minerals (× 400): 1-2 - Mica flakes; 3-4 - Shell fragments; 5-6 - Glauconite pellets; 7-8 - Carbonaceous detritus; 9-10 - Ferruginous materials; 11-12 - Pyrites

The lower paralic lithofacies unit (3521.96 – 3087.62 m) 434.34 m thick

The lower paralic lithofacies unit is predominantly shales with relatively thick sand intercalations. Sandstones are predominantly fine to medium grained, occasionally coarse to very coarse-grained. Sandstones are generally poorly to well sorted. The lower paralic lithofacies unit has thicker shale units compared to those found within the overlying upper paralic succession with average shale to the sand ratio of 80:20%. Two depositional subcycles A and B (Figure 6) were identified based on Gamma Ray Log patterns (fining up and coarsening up, Figures 4 & 5) and shale to the sand ratio (Selley 1978; Durugbo & Uzodimma 2013). Each sub-cycle consists predominantly of underlying shale, overlain by a thin sandstone unit. The subcycles are:

i. Subcycle A (3521.96 – 3215.64 m) 304.80 m thick

This is the lowermost section of the analysed interval. It is composed of a predominantly shaly lower section (3521.96 – 3319.27 m) overlain by a sandy interval (3319.27 – 3215.64 m). The shales are brownish grey, reddish brown to grey, platy, flaggy, and moderately hard. Lithologically, the sands are fine to medium grained, occasionally coarse to very coarse grained, moderately to well sorted and subangular to subrounded. Ferruginous materials and shell fragments occur in this subcycle. Mica flakes, carbonaceous detritus and pyrites are not common but fairly regular. The crescentic sands occurring over the intervals 3444.24 – 3429 m and 3422.90 – 3392.42 m are interpreted as channel/overbank lobes. Within the shales are symmetrical, cylinder and fining upwards sand units interpreted as offshore bars, distributary and tidal channels respectively (Sneider et al. 1978; Onyekuru et al. 2012), while the upper section of the subcycle (3319.27 – 3215.64 m) consisting of sands characterised by multiserrate cylinder and funnel shaped motifs indicative of distributary channel and subaqueous mouth bar deposits,were probably laid during aggradational and progradational episodes (Figures 4 and 5). Supporting these deductions is the co-occurrence of carbonaceous detritus, mica flakes and absence of glauconite pellets (Selley 1976).

ii. Subcycle B (3215.64 – 3087.62 m) 128.02 m thick

This 128.02 m thick sub-cycle is composed of hemipelagic shale with minor thin sand intercalations at the base (3215.64 – 3157.73 m), overlain by a sandy section (3157.73 – 3087.62 m). It constitutes the top of the lower paralic lithofacies unit. The shale is homogenous, reddish brown to grey, silty and flaggy to platy. The sands are milky white, predominantly fine to medium grained, occasionally coarse to very coarse grained, subangular to subrounded and moderately sorted. Rare to common ferruginous materials, shell fragments, rare mica flakes and carbonaceous detritus occur almost throughout the subcycle, while pyrite and glauconite pellets are few. The predominantly shaly/silty character of the lower part of the subcycle and the mixture of glauconite pellets and shell fragments suggest deposition in low energy, shallow marine settings (Selley 1978). The coarsening upward sands over intervals 3157.73 – 3163.82 m are interpreted as barrier bar deposits. The amplified sand unit of the upper section (3157.73 – 3087.62 m), consisting of sands exhibiting multiserrate cylinder and upward coarsening profile are interpreted as subaqueous channels and barrier bar deposits (Sneider et al. 1978; Onyekuru et al. 2012). This is further confirmed by the mixture of carbonaceous detritus and glauconite pellets (Selley 1978).

The upper paralic lithofacies Unit (3087.62 – 2197.61 m) 890.01 m thick

This lithofacies unit directly overlies the lower paralic succession. It consists predominantly of well-developed thick sandstone and few thinner shale intercalations. Sandstones are predominantly fine to medium grained, occasionally coarse to very coarse grained and granular. Sandstones are generally poorly to moderately sorted. Six (6) depositional sub-cycles were differentiated within this unit based on Gamma Ray Log patterns (fining up and coarsening up) and shale to the sand ratio (Selley 1978; Durugbo & Uzodimma, 2013). These are:

i. Subcycle C (3087.62 – 2929.13 m) 158.50 m thick

This subcycle starts with a thin silty shale unit (3087.62 – 3060.19 m), followed by a predominantly sandy sequence (3060.19 – 2929.13 m). The sands are predominantly fine to medium grained, occasionally coarse to granule sized and moderately sorted with deteriorating sorting over the upper section. The shales are reddish brown to grey, platy to flaggy and moderately hard. The subtle fining upward sands occurring over interval 3078.48 – 3072.38 m are most likely to be of tidal channel origin (Figure 4) (Sneider et al. 1978). The Gamma Ray Log motifs of the upper section (3060.19 – 2929.13 m) of this subcycle are essentially hybrid sand units exhibiting coarsening upward and multiserrate cylinder shaped grain size profiles interpreted as barrier bar to distributary channel associations (prograding complex) (Fig.

5) (Sneider et al. 1978). The persistence of ferruginous materials, carbonaceous detritus, glauconite pellets, and mica flakes suggest high energy deposition near the ancient shoreline (Selley 1976).

ii. Subcycle D (2929.13 – 2801.11 m) 128.02 m thick

This subcycle is composed of a thin shale unit (2929.13 – 2883.41 m) with minor sand intercalations, overlain by a sandy section (2883.41 – 2801.11 m). It has similar lithologic attributes with subcycle C discussed above. Accessories are dominated by ferruginous materials. Pyrites, shell fragments, carbonaceous detritus and mica flakes are rare. The predominantly shaly character of the lower part of the subcycle and the presence of ferruginous materials, carbonaceous detritus and pyrites are consistent with low energy, subwave, suboxic to anoxic, shallow marine settings (Selley 1978). Pyrites in the shale indicates the reducing conditions under which they were deposited **(**Adeniran 2014)**.** The poorly amplified sand units occurring over interval 2926.08 – 2916.94 m within the shales, exhibiting upward coarsening profiles is interpreted as subaqueous mouth bar deposits (Figure 4) (Sneider et al. 1978). The multiserrate cylinder/subtle bell with overall coarsening upward Gamma Ray Log motifs of the upper section (2883.41– 2801.11 m) and the presence of carbonaceous detritus may suggest tidal channel - subaqueous mouth bar associations for these sands (Selley 1978).

iii. Subcycle E (2801.11 – 2563.37 m) 237.74 m thick

This relatively thick subcycle is composed of a thin shale unit (2801.11 – 2740.15 m) with few sand breaks, overlain by a predominantly sandy interval (2740.15 – 2563.37 m). Lithologically, the sands are milky white, predominantly fine to medium grained, occasionally coarse to very coarse grained, moderately to well sorted and subangular to subrounded. The shales are brownish grey to grey, silty, platy and moderately hard. The accessory mineral suites are mostly ferruginous materials, carbonaceous detritus, shell fragments and mica flakes in decreasing order of abundance. These criteria indicate deposition in lower deltaic plain environments (Selley 1976). The slightly serrate cylinder-shaped sand units over intervals 2773.68 – 2758.44 m are interpreted as distributary channel deposits (Sneider et al. 1978; Onyekuru et al. 2012). The amplified sand unit of the upper section (2740.15 – 2563.37 m), consisting of multiple stacks of well-developed sands exhibiting cylinder-shaped profile is interpreted as distributary channel deposits (Sneider et al. 1978; Onyekuru et al. 2012). Supportive of this deduction is the occurrence of carbonaceous detritus in rare quantities while ferruginous materials are persistent (Selley 1978).

iv. Subcycle F (2563.37 – 2481.07 m) 82.30 m thick

This interval is composed of alternating sand and shale. The basal section (2563.37 – 2542.03 m) is essentially shaly, grading upwards into a sandier sequence (2542.03 –2481.07 m). The shales are brownish grey to dark grey and flaggy to platy. The sands are milky white to buff, predominantly fine to medium grained, occasionally coarse to very coarse grained, well sorted to moderately sorted and subangular to subrounded. The sand bodies occurring over the upper section of the sub-cycle (2542.03 – 2481.07 m), characterised by serrate cylinder and funnel-shaped motifs are interpreted as subaqueous channels and barrier bar deposits respectively (Sneider et al. 1978; Onyekuru et al. 2012). The co-occurrence of glauconite pellets and carbonaceous detritus lend credence to this interpretation (Selley 1978). Sediments of this sub-cycle are believed to have been laid down in coastal to inner shelf settings.

v. Subcycle G (2481.07 – 2301.24 m) 179.83 m thick

This relatively thick sub-cycle commences with a homogeneous (pelagic) shaly section (2481.07 – 2410.97 m), overlain by interbedded sands and shales (2410.97 –2301.24 m) with sands predominating. The homogeneous shale is grey, brownish grey to dark coloured, platy and moderately hard. The sands are milky white, predominantly fine to medium grained, occasionally coarse to very coarse grained and granular, moderately to poorly sorted and sub-angular to rounded. This subcycle recorded an increase in the abundance of ferruginous materials, carbonaceous detritus, shell fragments and mica flakes. This, coupled with shaly character of the lower section, suggest deposition in an oxygenated, low energy marginal marine environments (Selley 1978). The Gamma Ray Log motifs of the upper section (2410.97 – 2301.24 m) are hybrid sand units of serrate cylinder on funnels, and are most probably distributary channel – subaqueous mouth bar associations (Sneider et al. 1978; Onyekuru et al. 2012). This is corroborated by the presence of carbonaceous detritus and absence of glauconite pellets. Appearance of shell fragments may also suggest an infilling of the channel to shallower depth (Selley 1978).

vi. Subcycle H (2301.24 – 2197.61 m) 103.63 m thick

This interval is made up of a 39.62 m thick silty shale base (2301.24 – 2261.62 m), overlain by a predominantly sandy sequence (2261.62 – 2197.61 m). It constitutes the top of the upper paralic lithofacies sequence. The sands are fine to medium grained, occasionally coarse to granule sized, poorly to moderately sorted and sub-angular to rounded. The shales are grey to brownish grey, platy to occasional flaggy and moderately hard. Ferruginous materials, shell fragments and carbonaceous detritus occur in rare to common quantities while mica flakes are rare and restricted to intervals 2301.24 -2279.90 m. The predominantly shaly character of the lower section and the occurrence of ferruginous materials and shell fragments are consistent with low energy, sufficiently oxygenated, shallow water settings (Selley 1978). The multiserrate cylinder-shaped sands over the upper section (2261.62 – 2197.61 m) are most probably distributary channels (Sneider et al. 1978; Onyekuru et al. 2012). The presence of carbonaceous detritus and absence of glauconite pellets lend credence to this interpretation (Selley 1978). The increase in sand percentage suggests relative shallowing or tremendous shallow water clastic influx. The depositional environment probably shallowed from base to top.

The paralic succession of Ida-5 Well (3532.63 – 2206.75 m)

This interval is essentially a heterogeneous succession of alternating sand and shale/ siltstone units. The regular pattern of sand and shale/siltstone intercalations permits easy recognition on the Gamma-Ray Log of eight subcycles (autocycles) of sedimentation within the paralic succession. Each of these subcycles commences with a relatively thick marine shale/silt and progressively shallows into fluviomarine/fluviatile sands. The recognised sub-cycles are presented in figure 7. The paralic sequence in Ida-5 has been subdivided into two major lithofacies sequences, which are:

i. The lower paralic unit (3532.63 – 3179.06 m), and
ii. The upper paralic unit (3179.06 – 2206.75 m).

The lower paralic lithofacies unit (3532.63 – 3179.06 m) 353.57 m thick

This consists predominantly of shale with relatively thick sandstone intercalations.

Sandstones are predominantly fine to medium grained, occasionally coarse to very coarse grained. Sandstones are generally poorly to well sorted. Compared with Ida-4, two depositional subcycles A and B, were identified (Figure 7).

Each subcycle consists of underlying predominantly shaly (transgressive) phase, overlain by a sandy sequence. These are:

i. Subcycle A (3532.63 – 3358.90 m) 173.74 m thick

This is the lowermost section of the analysed interval and is composed of thick hemipelagic shales (3532.63 – 3389.38 m), overlain by a poorly developed sandy interval (3389.38 – 3358.90 m). The shales are brownish grey to dark grey, platy to flaggy and moderately soft to moderately hard with, gritty and fairly hard siltstone. The accessory mineral suites recovered over the subcycle consist of ferruginous materials and shell fragments. They occur in rare to common quantities. The predominantly shaly/sandy shale character of the lower section and the presence of ferruginous materials and shell fragments suggest deposition in low energy, oxic, shallow marine settings (Selley 1976). The thin symmetrical shaped sands within the shales are interpreted as offshore bars. The typical poorly developed crescentic-shaped log character of the upper section (3389.38 – 3358.90 m) interpreted as channel/overbank lobes, suggest intermittent medium to high energy burst into the depositional basin (Sneider et al. 1978). This may explain also the presence of ferruginous materials and shell fragments in the sub-cycle (Selley 1978).

ii. Subcycle B (3358.90 – 3179.06 m) 179. 83 m thick

This 179.83 m thick subcycle is composed of shaly lower section (3358.90 – 3267.46 m) with thin sand intercalations, overlain by a sandy sequence (3267.46 – 3179.06 m). It constitutes the top of lower paralic lithofacies unit. The shales are brownish grey to grey, silty, platy and moderately hard. The sands are milky white, fine to medium grained, occasionally coarse to very coarse grained and granular, subangular to rounded and moderately to poorly sorted. Rare to common occurrences of ferruginous materials and shell fragments characterise the subcycle. The predominantly shaly character of the lower section and the occurrence of ferruginous materials and shell fragments are consistent with low energy, oxygenated, shallow marine to coastal deltaic settings (Selley 1978). The poorly developed genetic sands occurring over intervals 3331.46 – 3322.32 and 3282.70 – 3273.55 m within the shales, exhibiting upward fining profiles are interpreted as tidal channel deposits. The Gamma Ray Log character of the sands of the upper section (3267.46 – 3179.06 m), suggest that the sand units exhibiting multiserrate cylinder/slightly serrate cylinder grain size profile are most probably distributary channel deposits of the lower deltaic plain (Sneider et al. 1978; Onyekuru et al. 2012).

The upper paralic lithofacies unit (3179.06 – 2206.75 m) 972.31 m thick

This lithofacies unit directly overlies the lower paralic sequence, with heterogenous succession of alternating sand and shale units. These consist predominantly of well-developed thick sands and few shaly intervals (Figure 7). Sandstones are predominantly fine to medium grained, occasionally coarse to very coarse grained and granular. Sandstones are generally poorly to moderately well sorted. Six depositional subcycles (authocyles) were differentiated within this unit. These are: -

i. Sub-cycle C (3179.06 – 2983.99 m) 195.07 m thick

This sub-cycle starts with a thin silty shale unit (3179.06 – 3130.30 m), overlain by a predominantly sandy sequence (3130.30 – 2983.99 m). The sands are predominantly fine to medium grained, occasionally coarse to very coarse grained and granular and moderately to poorly sorted. The shales are grey, dark grey to brownish grey, platy to flaggy and moderately hard. The cylinder-shaped sand unit occurring over interval 3166.87 – 3143.36 m is interpreted as distributary channel (Onyekuru et al. 2012). The Gamma Ray Log motifs of the upper section (3130.30 – 2983.99 m) of this sub-cycle are essentially amplified sand units exhibiting multiserrate cylinder shaped profiles interpreted as distributary channels and indicates prograding shorelines (Onyekuru et al. 2012). This is corroborated by the presence of carbonaceous detritus, ferruginous materials, shell fragments and restricted glauconite pellets (Selley 1978).

ii. Sub-cycle D (2983.99 – 2825.50 m) 188.50 m thick

This subcycle is composed of a shaly interval (2983.99 – 2907.80 m) with minor sand intercalations, overlain by a stack of sands (2907.80 –2825.50 m). As in Ida-4, it has similar lithologic attributes with sub-cycle C discussed above. Accessories minerals are dominated by ferruginous materials. Also, as in Ida-4, carbonaceous detritus, shell fragments, mica flakes and pyrites are few. The predominantly shaly character of the lower section and the mixture of few ferruginous materials, pyrites and carbonaceous detritus suggest deposition in a low energy, sub-wave, suboxic to anoxic, shallow marine settings (Selley 1978). The crescentic sands occurring over interval 2971.80 –2956.56 m within the shales is interpreted as channel overbank lobes (Onyekuru et al. 2012). The sand unit of the upper section (2907.80 –2825.50 m) consisting of stack of sands exhibit cylinder-shapedped profile is interpreted as distributary channel deposits. Presence of shell fragments, carbonaceous detritus and pyrites lend credence to this interpretation (Selley 1978). Sediments of this sub-cycle are believed to have been laid down in coastal deltaic to inner shelf environments.

iii. Subcycle E (2825.50 – 2572.51 m) 252.98 m thick

This relatively thick sub-cycle is composed of a thin shale unit (2825.50 – 2764.54 m) with few sand breaks, overlain by a predominantly sandy sequence (2764.54 – 2572.51 m). Lithologically, the sands are milky white to smoky, predominantly fine to medium-grained, occasionally coarse to granule-sized, sub-angular to rounded and poorly to moderately well-sorted. The shales are grey to brownish grey, silty, platy to flaggy, and moderately hard. The accessory mineral suites are mostly ferruginous materials, carbonaceous detritus, shell fragments and mica flakes in decreasing order of abundance (Selley 1978). These criteria indicate deposition in lower deltaic plain environments. The poorly developed amplified sand units occurring over intervals 2802.64 – 2785.87 m is interpreted as tidal channel deposits. The typical multiserrate cylinder/cylinder shaped log characters of the upper section (2764.54 – 2572.51 m) are most likely distributary channel deposits (Onyekuru et al. 2012). Further supporting these deductions, is the presence of carbonaceous detritus and absence of glauconite pellets (Selley 1978).

iv. Subcycle F (2572.51 – 2490.22 m) 82.30 m thick

As in Ida-4, this interval is composed of alternating sand and shale. The basal section is essentially shaly (2572.51 – 2554.22 m), grading upward into a sandier sequence (2554.22 – 2490.22 m). The sands are very fine to medium grained, occasionally coarse/ very coarse grained and well to moderately well-sorted. The shales are grey, brownish grey to grey and platy to flaggy. Ferruginous materials and carbonaceous detritus occur in rare quantities with the disappearance of shell fragments throughout the subcycle. This suggests deposition in an oxygenated, high energy, marine environment (Selley 1978). The sand bodies of the upper section (2554.22 – 2490.22 m), characterised by cylinder and bell-shaped motifs are interpreted as distributary channel and tidal channel deposits respectively (Sneider et al. 1978; Onyekuru et al. 2012). Supporting these deductions are the occurrence of carbonaceous detritus and absence of glauconite pellets (Selley 1978).

v. Subcycle G (2490.22 – 2307.34 m) 182. 88 m thick

This relatively thick subcycle commences with a monotonously shaly lower section (2490.22 – 2420.11 m), overlain by a sandier interval (2420.11 – 2307.34 m). Though Gamma Ray Log character indicates good shale development, complimentary ditch cutting sample description is contradictory and suggests the presence of a thick shaly sand sequence. This discrepancy has been attributed to downhole caving or lag time errors. The sands are fine to medium grained, occasionally coarse to granule sized, poorly to moderately sorted and subangular to rounded. The typical multiserrate cylinder and funnel-shaped log character coupled with the persistence of carbonaceous detritus, ferruginous materials and sudden appearance of shell fragments in the upper part of the sub-cycle (2420.11 – 2307.34 m), may suggest a distributary channel and subaqueous mouth bar for these sands (Selley 1978).

vi. Subcycle H (2307.34 – 2206.75 m) 100.58 m thick

This interval commences with a 42.67 m thick shaly unit (2307.34 – 2264.66 m), overlain by a predominantly sandy sequence (2264.66 – 2206.75 m). It constitutes the top of the upper paralic lithofacies sequence. The sands are fine to medium-grained, occasionally coarse to very coarse-grained and granular, mostly sub-angular to subrounded and poorly to moderately-sorted. The shales are grey, platy to flaggy and moderately hard. Few ferruginous materials, carbonaceous detritus and rare pyrites occur almost throughout the sub-cycle with spotty records of mica flakes and shell fragments over interval 2225.04 – 2206.75 m. The predominantly shaly character of the lower section and the occurrence of ferruginous materials, pyrites and shell fragments are consistent with low energy, subwave and suboxic to anoxic, nearshore coastal deltaic settings (Selley 1978). The multiserrate cylinder-shaped sands over the upper section (2264.66 – 2206.75 m) are most probably distributary channels (Onyekuru et al. 2012). The presence of carbonaceous detritus and absence of glauconite pellets lend credence to this interpretation (Selley 1978). The increase in sand percentage suggests relative shallowing or tremendous shallow water clastic influx. The depositional environment probably shallowed from base to top.

The paralic succession of Ida-6 Well (4050.79 – 2679.19 m) 1371.60 m thick

This interval is essentially a heterogeneous sequence of alternating sand and shale/siltstone units. The regular pattern of sand and shale/siltstone intercalations permits easy recognition (on logs) of seven subcycles (authocycles) of sedimentation within the upper paralic and lower paralic sequence. Each of these sub-cycles commences with a relatively thick marine shale/silt and progressively shallows into fluviomarine /fluviatile sands. The recognised subcycles are as summarised in Figure 8. The paralic sequence of Ida-6 has been subdivided into two major lithofacies sequences, these are:

i. The lower paralic unit (4050.79 – 3529.58 m), and
ii. The upper paralic unit (3529.58 – 2679.19 m).

The lower paralic lithofacies unit (4050.79 – 3529.58 m) 521 21 m thick

The lower paralic lithofacies unit is predominantly shales with relatively thick sandstones intercalations. Sandstones are very fine to medium grained, occasionally coarse grained.

Sands are generally well sorted. Compared with Ida-4 and 5, two depositional subcycles A and B (Figure 8) were identified. Each subcycle consists of underlying predominantly shaly (transgressive) phase, overlain by a thick sandy (regressive) phase. These subcycles are:

i. Sub-cycle A (4050.79 – 3694.18 m) 356.61 m thick

This is the lowermost section of the analysed interval and is composed of a predominantly shaly lower section (4050.79 – 3840.48 m) with silty sand intercalations, overlain by a sandy interval (3840.48 – 3694.18 m). The 210.31 m shales are reddish brown, brownish grey to dark grey, silty, papery to platy and moderately soft to moderately hard. The sands are very fine to medium grained, occasionally coarse grained, mostly subangular and well sorted. Ferruginous materials and carbonaceous detritus characterised the sequence. The predominantly shaly/silty character of the lower part of the subcycle and the mixture of ferruginous materials and carbonaceous detritus suggest deposition in a low energy, oxic, shallow marine settings (Selley 1978). The fining upward sands occurring over intervals 3936.80 – 3925.82 and 3886.20 – 3877.06 m are interpreted as tidal channels (Sneider et al. 1978; Onyekuru et al. 2012). Also occurring over intervals 3992.88 – 3953.26 m within the shales is a stack of upward coarsening sands interpreted as subaqueous mouth bars. The coarsening upward textural pattern of the sands of the upper section (3840.48 – 3694.18 m) exhibited by multiserrate funnel, cylinder/subtle bell-shaped Gamma Ray Log profiles interpreted as subaqueous mouth bars and distributary channel deposits indicates prograding shoreline (Sneider et al. 1978; Onyekuru et al. 2012). Supporting these deductions is the presence of carbonaceous detritus and absence of glauconite pellets (Selley 1978).

ii. Subcycle B (3694.18 – 3529.58 m) 164.60 m thick

This subcycle is composed of shale with thin sand intercalations (3694.18 – 3617.98 m), overlain by a stack of sands (3617.98 – 3529.58 m). It constitutes the top of the lower paralic lithofacies sequence. The shale/mudstones are homogenous, grey to brownish grey, flaggy to platy and moderately hard. The sands are very fine to medium –grained, occasionally coarse –grained, sub-angular to sub-rounded and well sorted. Index minerals and accessories are dominated by ferruginous materials. Shell fragments are rare and localised to the upper section (3611.88 – 3529.58 m). The predominance of shales over the lower part of the sub-cycle and the presence of ferruginous materials indicate deposition in low energy, sufficiently oxygenated, shallow to relatively deep marine settings (Selley 1978). The finning upwards sand occurring over intervals 3617.98 – 3602.74 m is interpreted as tidal channels. The amplified sand units of the upper section (3617.98 – 3529.58 m), consisting of stack of sands exhibiting upward coarsening profile is interpreted as a subaqueous mouth bar build-up (Sneider et al. 1978; Onyekuru et al. 2012).

The upper paralic lithofacies unit (3529.58 – 2679.19 m) 850 39 m thick

This lithofacies unit directly overlies the lower paralic unit. This consists predominantly of regular alternation of well-developed thick sandstones and relatively thick shales intervals in near equal proportion (Figure 8). Sandstones are predominantly very fine to medium grained, occasionally coarse to very coarse grained/granule sized. Sandstones are moderately sorted to well sorted. Five depositional subcycles were differentiated within this unit. These are:

i. Subcycle C (3529.58 – 3322.32 m) 207.26 m thick

This subcycle starts with a thin silty shale unit (3529.58 – 3496.05 m), followed by a predominantly sandy sequence (3496.05 – 3322.32 m). Over this subcycle with good sand development on Gamma Ray Log, complementary lithological descriptions of ditch cutting samples suggest a thick shale/sandy shale section. These seemingly contradictory observations may be attributed to lag time errors or sample mixing. The sands are predominantly fine to medium grained, occasionally coarse/very coarse grained, subangular to sub-rounded and generally well sorted. The shales are grey, brownish grey to dark grey, silty, platy and moderately soft to moderately hard. The subtle crescentic sands occurring over interval 3520.44 – 3505.20 m are most likely to be of channel/overbank lobes origin (Onyekuru et al. 2012). The Gamma Ray Log motifs of the upper section (3496.05 – 3322.32 m) of this sub-cycle are amplified sand units exhibiting multiserrate cylinder shaped grain size profiles interpreted as distributary channel deposits (prograding shoreline). The presence of ferruginous materials, carbonaceous detritus, shell fragments and mica flakes suggest high energy, oxic deposition in close proximity to the ancient shoreline (Selley 1978).

ii. Subcycle D (3322.32 – 3133.34 m) 188.98 m thick

This subcycle is composed of a shaly interval (3322.32 – 3238.50 m) with minor sand intercalations, overlain by a sandy section (3238.50 – 3133.34 m). The shales are reddish brown to grey, silty, flaggy to platy and moderately soft to moderately hard. The sands are milky white to smoky, predominantly fine to medium grained, occasionally coarse to very coarse grained, moderately to well sorted and subangular to subrounded. Index minerals are dominated by ferruginous materials and shell fragments. Carbonaceous detritus showed spotty occurrences. The predominantly shaly character of the lower section and the presence of ferruginous materials and shell fragments are consistent with low energy, sufficiently oxygenated, shallow water settings (Selley, 1978). The poorly developed sand units occurring over the interval 3313.18 – 3297.94 m within the shales exhibiting coarsening upwards profile is interpreted as subaqueous mouth bar deposits (Sneider et al. 1978; Onyekuru et al. 2012). The slightly serrate cylinder on funnel shaped log character of the upper section (3238.50 – 3133.34 m) and the presence of carbonaceous detritus and absence of glauconite pellets may suggest a distributary channel subaqueous mouth bar associations origin for these sands (Selley 1978). The appearance of shell fragments may also suggest an infilling of the channel to shallower depth (Selley 1978).

iii. Sub-cycle E (3133.34 – 2831.59 m) 301.75 m thick

This relatively thick offlap sub-cycle is composed of a thin shale unit (3133.34 – 3057.14 m) with few sand breaks, overlain by a predominantly sandy interval (3057.14 – 2831.59 m). Lithologically, the sands are milky white, very fine to medium grained, occasionally coarse to very coarse grained/granule sized, poorly to well sorted and sub-angular to subrounded. The shales are reddish brown to grey, silty, platy and moderately soft to moderately hard. The accessory mineral suites are mostly ferruginous materials, shell fragments, carbonaceous detritus and mica flakes in decreasing order of abundance. These criteria indicate deposition in lower deltaic plain environments (Selley 1978). The slightly serrate cylinder and symmetrical shaped sand units over intervals 3108.96 – 3093.72 and 3087.62 – 3084.58 m within the shales are interpreted as distributary channel and offshore bar deposits respectively (Sneider et al. 1978; Onyekuru et al. 2012). The amplified/genetic sand units of the upper section (3057.14 – 2831.59 m), consisting of multiple stacks of well-developed sands exhibiting cylinder-shaped profiles are interpreted as distributary channel deposits. Supportive of this deduction is the occurrence of carbonaceous detritus and absence of glauconite pellets, while ferruginous materials are ubiquitous (Selley 1978).

iv. Subcycle F (2831.59 – 2755.39 m) 76.20 m thick

This short subcycle commences with a thin monotonously shale unit (2831.59 – 2798.06 m), overlain by a poorly developed regressive sandy section (2798.06 – 2755.39 m). This sandy section is more pronounced in Ida-4 and 5. The sands are very fine to medium grained, occasionally coarse grained and well sorted. The shales are reddish brown to grey, papery to platy and moderately hard. Abundant ferruginous materials, few shell fragments, rare mica flakes and carbonaceous detritus were recorded almost throughout the subcycle. The predominantly shaly character and very fine-grained nature of the sands suggest depositon at some considerable distance far from sediment source area possibly in a low energy, shallow to relatively deep marine environmental settings (Selley 1978). The sand bodies of the upper section (2798.06 –2755.39 m), characterised by poorly developed crescentic shaped motifs are interpreted as channel/overbank lobes (Sneider et al. 1978; Onyekuru et al. 2012).

v. Subcycle G (2755.39 – 2679.19 m) 76.20 m thick

This subcycle was not fully analyzed. Unlike Ida-4 and 5, only the shaly lower section was analysed. The incomplete subcycle consists of only the hemipelagic shale unit (2755.39 – 2679.19 m), while the overlying sandy unit was not analysed. The shales are homogenous, reddish brown to grey, platy and moderately hard. Ferruginous materials and shell fragments characterised the sequence. The accessory mineral assemblage and the shaly character of the section suggest deposition in a low energy, marginal marine setting with oxidizing condition (Selley 1978).

Lithofacies correlation of Ida-4, 5 and 6 Wells

The lithologic/lithofacies correlation established the linkage of units of similar lithology and stratigraphic position in the three studied wells. A good correlation was established between most of the subcycles in Ida-4, 5 and 6 wells. The similarities in the Gamma-Ray Log patterns aided the lithofacies correlation. The various lithofacies succession subcycles identified correlate with their equivalents in Ida-4, 5 and 6 wells (Figure 10). The lithology and differences in depth at which they correlate shows that Ida-6 well is more distal and far deeper than Ida-4 and 5 wells (Figure 10).

Interestingly, in subcycle A within the lower paralic lithofacies sequences, the 134.11 m thick sandstone unit penetrated between 3319.27 – 3215.64 m in Ida-4 which is equivalent to 146.30 m thick sandstone unit penetrated between 3840.48 – 3694.18 m in Ida-6 is not seen in Ida-5, or may be its remnant is what is seen between 3389.38 – 3358.90 m. This suggests possibility of minor faulting in Ida-5 well or sediment by-pass or part of the sandstone unit has been eroded. This could be due to local erosion and redistribution of sediments (Reijers 2011). However, above subcycle A, correlation of the three wells is consistent (Figure 10). The correlation depicts the lateral continuity and geometry of the lithofacies units within the field. This is essential in hydrocarbon exploration. Rapid sedimentation rates are inferred in the studied area on the basis of the observed alternation of thick sandstone and shale/mudstone units (paralic section).

Sequence stratigraphy

In this study, one Maximum Flooding Surface, Transgressive Surface, Sequence Boundary, Lowstand Systems Tracts, Transgressive Systems Tracts and two Highstand Systems Tracts were identified within the studied intervals in the three wells. These identified Systems Tracts consist of autocyclic cycles of sedimentary successions described as subcycles under sections 5.1, 5.2 and 5.3. The identified systems tracts followed the Genetic Sequence Model (Genetic Stratigraphic Sequences, consisting of strata bounded by Maximum Flooding Surfaces) of Galloway (1989). The work of these authors guided the identification of the system tracts and their bounding surfaces (Poumot, 1989; Vail and Wornardt, 1991; Armentrout, 1991; Tyson, 1995; Reijers *et al*., 1996; Batten and Stead, 2005; Thomas *et al*., 2015; Adojoh *et al.*, 2015: Olayiwola and Bamford, 2016).

Condensed Sections (CS) and Maximum Flooding Surfaces (MFS)

Condensed sections are thin marine beds of hemipelagic and pelagic sediments deposited at very slow rates which are mostly areally extensive in the time of maximum regional transgression of the shoreline (Reijers *et al*., 1996)

The condensed sections are recognised at 2426 – 2430 m, 2440 – 2454 m and 2734 - 2816 in Ida-4, 5 and 6 wells respectively. The bases for their recognition are:

i. There are abundant and diverse recoveries of pollen and spores. The associated palynomacerals are more occurrences of small sized palynomacerals 1 and 2 with scanty presence of large sizes. PM 3, PM 4 and amorphous organic matter were not recovered within the intervals (Figures 11, 12 and 13); and
ii. The lithology is basically shale, deduced from the ditch cutting samples and Gamma Ray Log motifs (Figures 11, 12 and 13).

The Maximum Flooding Surfaces (MFS) represent the fullest areal development (apex) of a major condensed section where marine influence has encroached the greatest distance beyond the shelf. They are recognised at 2430 m, 2445 m and 2761 m in the Ida-4, 5 and 6 wells respectively (Figures 11, 12 and 13). The surfaces are considered as the shaliest point within the condensed sections as deduced from the Gamma Ray Log (110, 70 and 150 API for Ida-4, 5 and 6 wells respectively). The associated palynofacies consists of diverse and abundant pollen, spore, abundant small and medium sized PM 1 and 2 and few occurrences of large sized PM 1 and 2; The surfaces are dated 9.5 Ma by correlation to the Niger Delta Cenozoic Chronostratigraphic Chart which contains the eustatic curves of Vail (1987) and the global sea level cycles of Haq *et al*. (1988). The MFS that falls between P780 and P820 in the Niger Delta pollen zones contained in the Niger Delta Cenozoic Chronostratigraphic Chart is 9.5 million years. The 9.5 Ma Maximum Flooding Surface is in the third order cycle within eustatic curves of Vail (1987) and the global sea level cycles of Haq *et al*. (1988).

Sequence Boundaries (SB)

Sequence Boundaries refer to the erosional (unconformity) surfaces bounding depositional sequence. They are formed during the relative lowering and during lowstand of sea level. Sequence Boundaries were recognised at 2880 m, 2910 m and 3240 m in Ida-4, 5 and 6 wells respectively (Figures 11, 12 and 13) and are dated 10.35 Ma because of the following reasons:

i. There is decrease (few or scarce) in pollen, spores and palynomacerals recoveries at these depths (Figures 11, 12 and 13);
ii. From the logs (Gamma Ray Log and Deep Induction Resistivity Log), it is the point of change (sharp lithologic contact) between coarsening upward (forestepping) HST and the fining upward (backstepping) TST (Reijers *et al*., 1996);
iii. It is dated 10.35 Ma because of its stratigraphic position in the sequence. The SB immediately below the 9.5 Ma MFS is 10.35 Ma in the correlation of palynostratigraphic zones to the Niger Delta Cenozoic Chronostratigraphic chart.
iv. The surfaces are truncated on the seismic section suggesting erosional truncation and type-1 sequence boundary (Figures 13 and 14).

Systems Tracts

Three Systems Tracts namely: Highstand Systems Tract (HST), Trangressive Systems Tract (TST) and Lowstand Systems Tract (LST) were recognised in the studied sections of the three wells.

Highstand Systems Tract (HST)

It is the stratigraphic interval deposited during a relative decrease in sea level between the MFS and the overlying SB (Boggs, 2006);

In Ida- 4, HST was identified from 3496 – 2880 m and 2430 – 2152 m. In Ida-5, the intervals from 3569 – 2910 m and 2445 - 2202 m were recognised as HST. In Ida-6, the intervals from 4051 – 3240 m and 2761 - 2679 m were identified as HST (Figures 11, 12 and 13). The delineated HSTs consist of subcycles (autocycles) A, B, C, part of subcycle D, subcycles G and H. The reasons for these identifications were as follows:

i. From the logs, the lithology is composed of alternation of sand and shale/mudstones intervals (Figures 11, 12 and 13);
ii. The logs show overall coarsening upwards and shallowing upward (progradational - aggradational) sequences;
iii. The intervals are bounded by MFS at the bottom and SB at the top (Figures 11, 12, 13, 14 and 15);
iv. There are few to zero occurrence of savannah and montane taxa with relative increase in fresh water and mangrove taxa and
v. The palynomaceral present are not degraded. This is evident in the absence of highly degraded PM 4 (Thomas *et al*., 2015) and there are more occurrence of small and medium sized PM 1 and 2, although there are few occurrences of the large sizes (Figures 11, 12 and 13).

Transgressive Systems Tract (TST)

TST is deposited during the relative rise of sea level and persists until the maximum relative rise of sea level is released at the MFS. Condensed section allows easy correlation.

TSTs were recognised at the depth intervals of 2800 – 2430 m, 2829 – 2445 m and 3135 – 2761 m in Ida-4, 5 and 6 wells respectively. The recognised TSTs consist of part of subcycle (autocycles) D, subcycles E and F. The reasons for these recognitions are as follows:

i. From the logs, the sequence within the intervals displayed overall fining upward sequence. The lithology is composed of sand overlain by fossiliferous pelagic shale (Figures 11, 12 13, 14 and 15);
ii. The sequences are bounded at the top by MFS and below by Transgressive Surface;
iii. The palynofacies association consists of slight decrease occurrence of PM 1 and 2 with scanty occurrence of PM 3 and 4 in few intervals. There is high representation of coastal miospores (mangrove, freshwater and rainforest taxa) compared to minimal hinterland savanna and montane taxa (Olayiwola and Bamford, 2016).
iv. On the seismic section was observed landward onlap stratal stacking pattern.

Lowstand Systems Tract (LST)

LST represents lowstand prograding complexes deposited during the slow relative rise of sea level at or near shelf margin (Vail and Wornardt, 1991).

LSTs were recognised at 2880 – 2800 m, 2910 – 2829 m and 3240 – 3135 m in Ida-4, 5 and 6 wells respectively. They occurred in subcycle D and were recognised because of the following:

i. From the logs, the intervals show serrated block shaped pattern, Low Gamma Ray values (5 – 30 API) and overall coarsening up parasequence indicating channel sandstone deposit (Figures 11, 12, 13, 14 and 15);
ii. The palynofacies association consists of low abundance of miospores especially the mangrove, freshwater and rainforest taxa and increased occurrence of montane and savannah taxa (fungal spores, *Monoporite annulatus, Coryius* sp. and *Pteris* sp.). The palynomacerals 1 and 2 that occur are more of large and medium sizes than the small size (Tyson, 1995; Batten and Stead, 2005) (Figures 11, 12 and 13);
iii. The intervals are bounded at the top and bottom by Transgressive Surface (TS) and Sequence Boundary (SB) respectively.
iv. On the seismic section, the intervals show continuous basinward reflection.

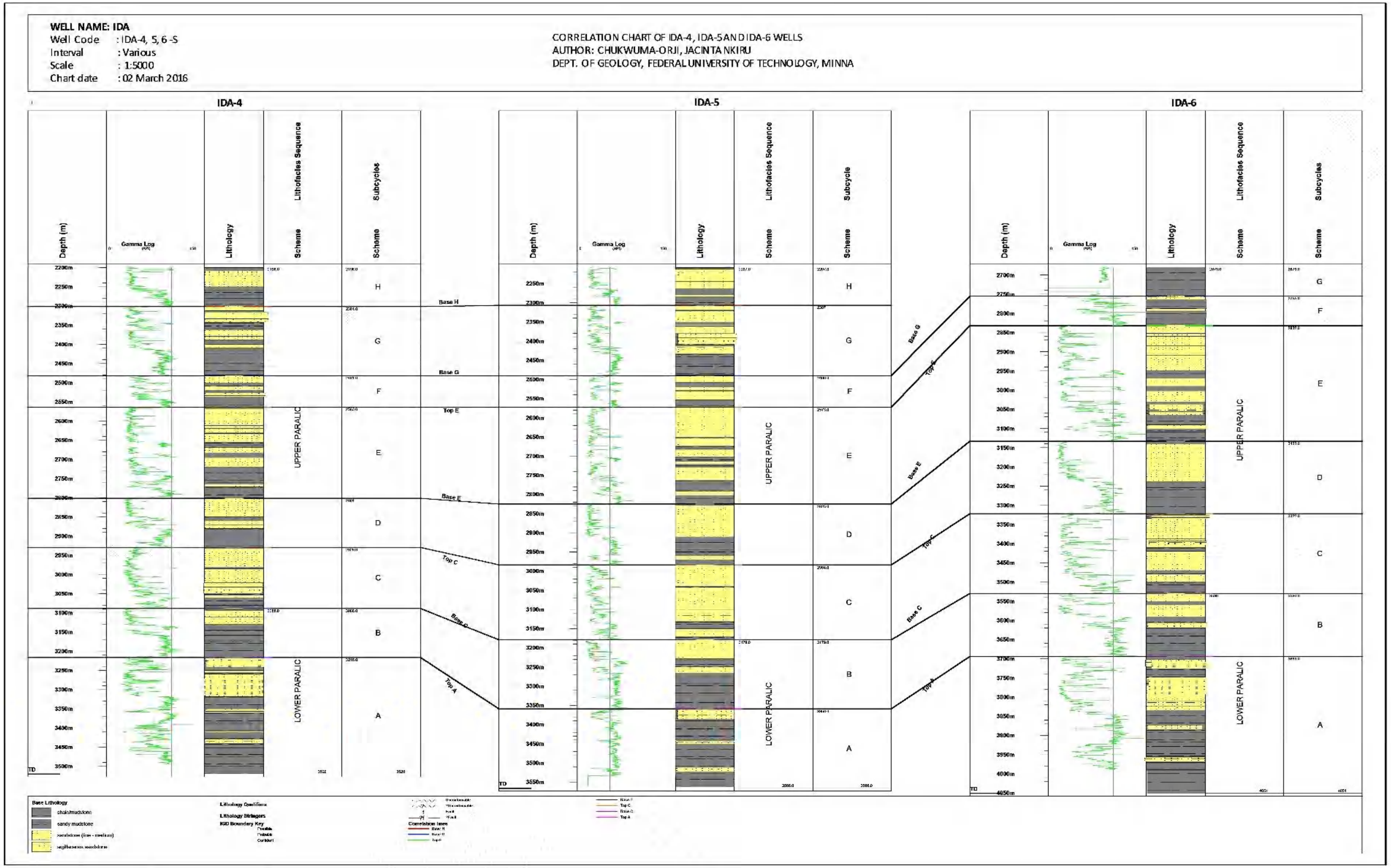

Figure 10: Lithofacies correlation chart of Ida-4, 5 and 6 wells

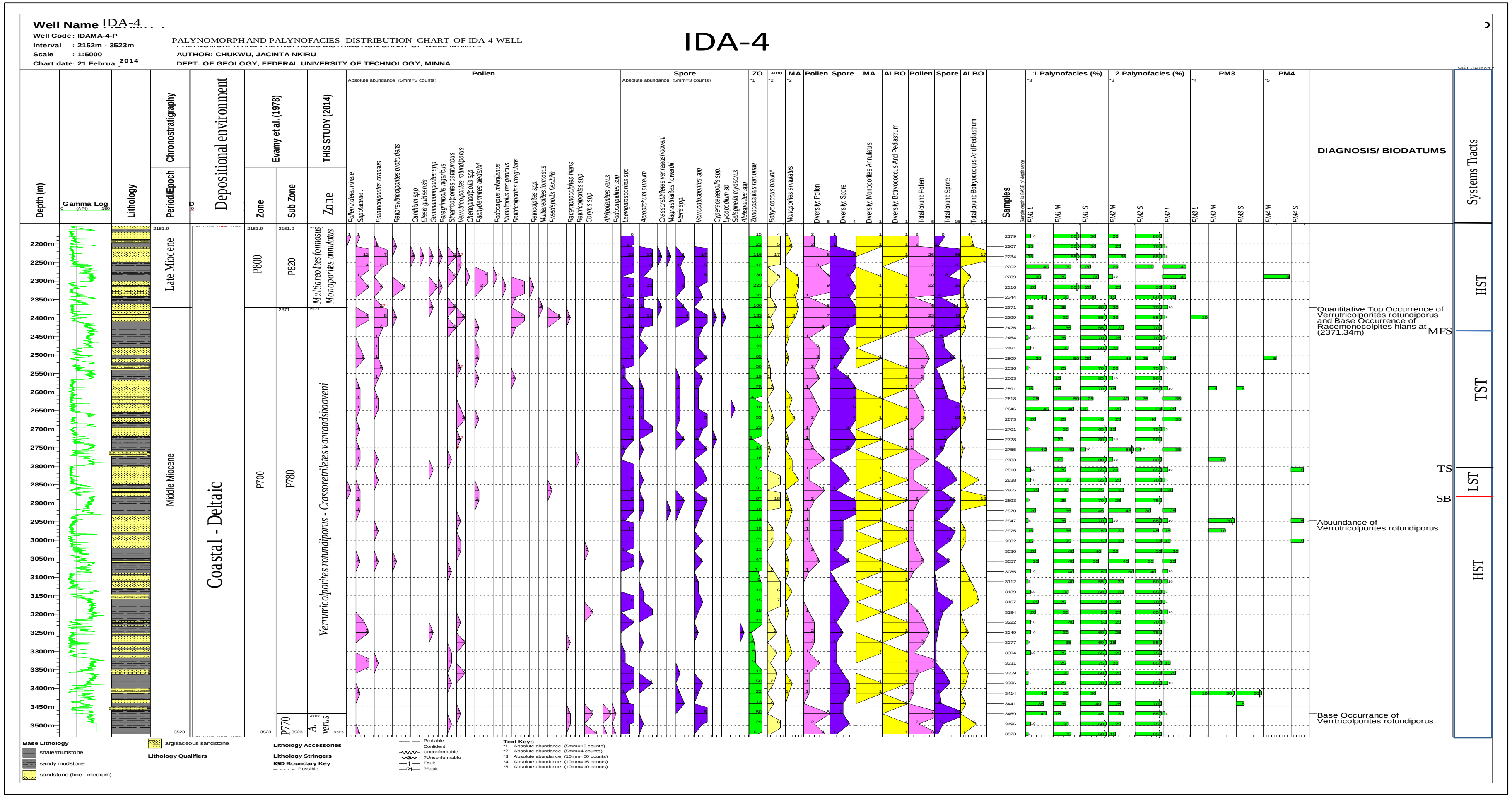

Figure 11: Palynofacies distribution and delineated systems tracts of Ida-4 well

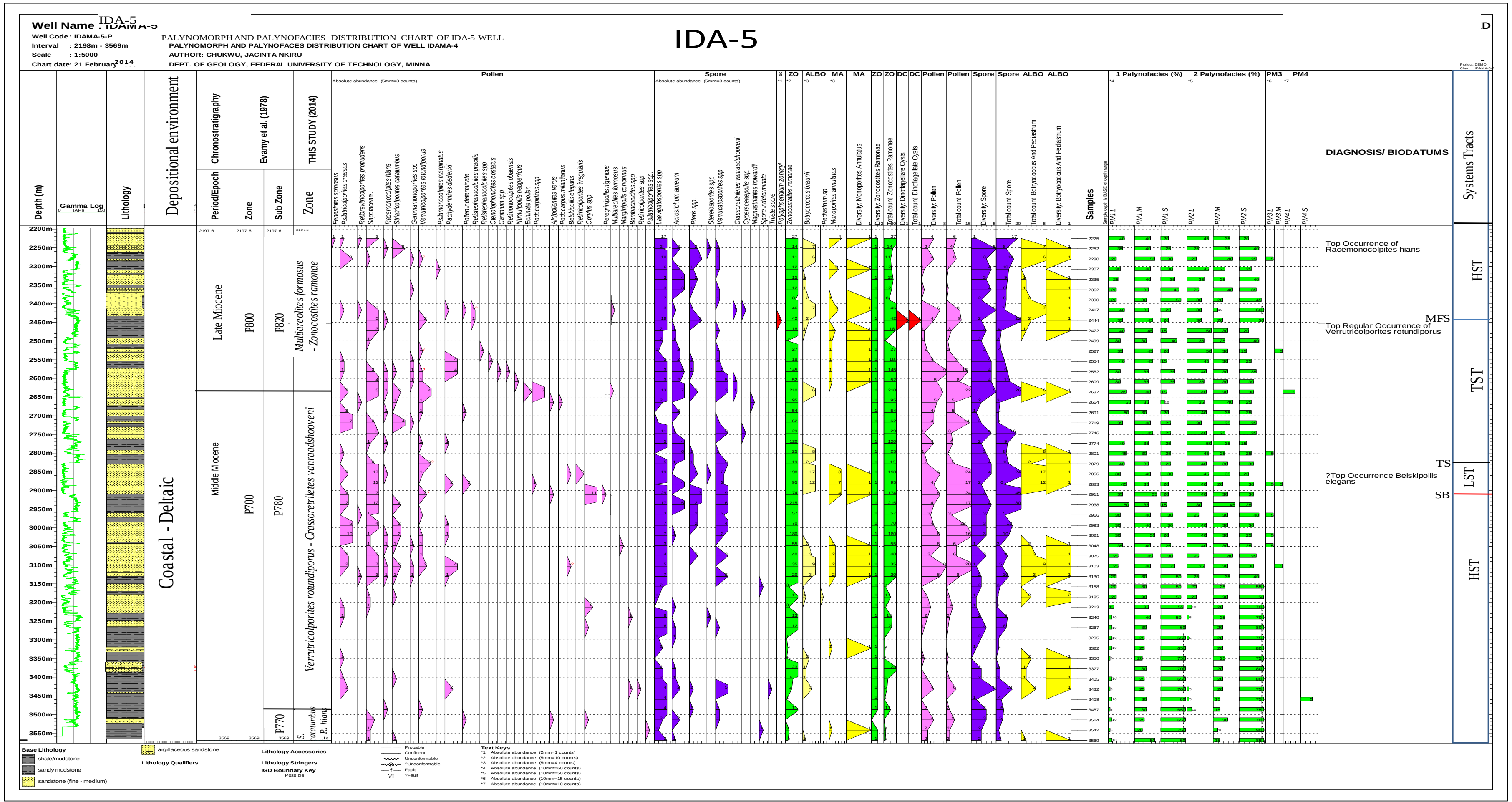

Figure 12: Palynofacies distribution and delineated system tracts of Ida-5 well

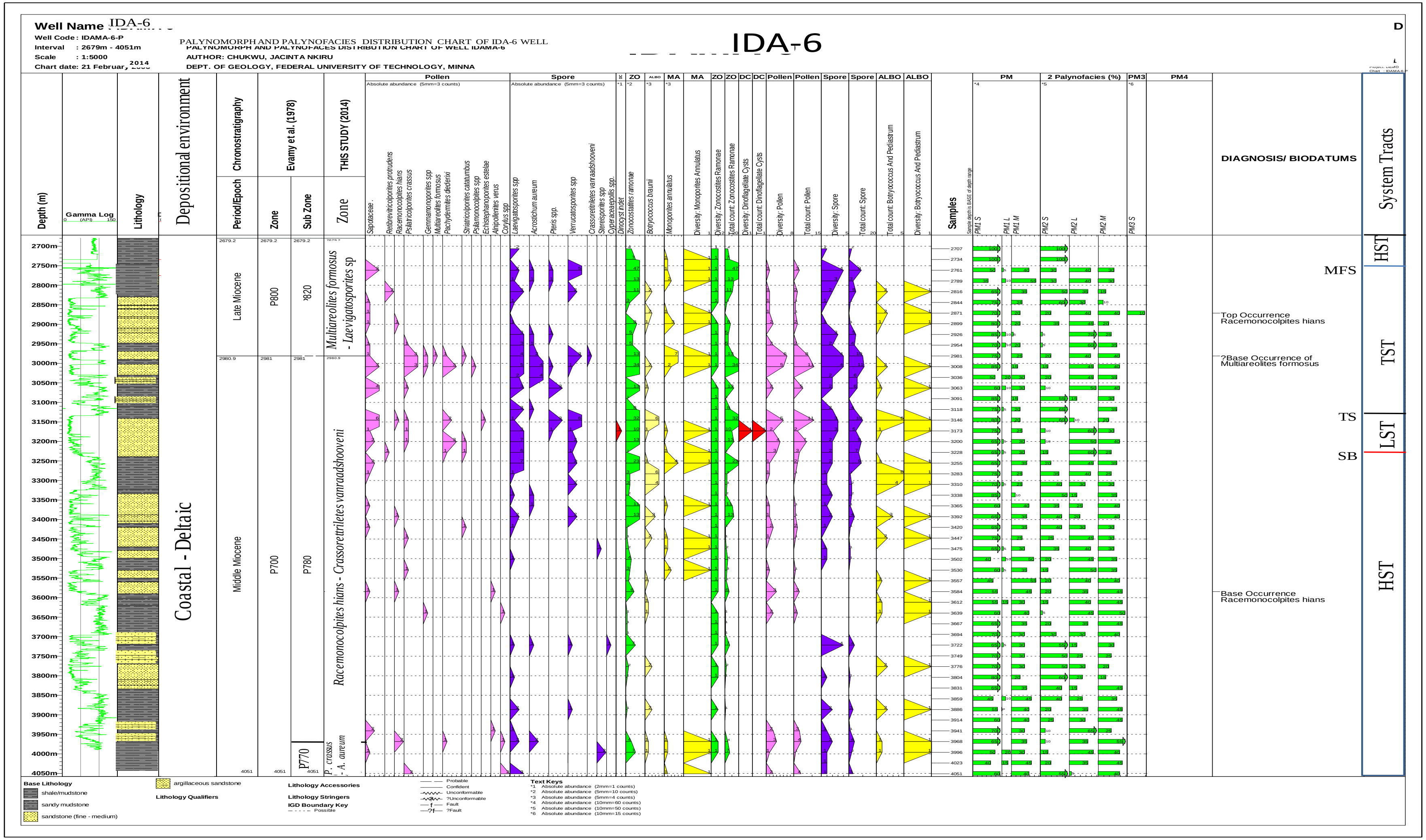

Figure 13: Palynofacies distribution and delineated system tracts of Ida-6 well

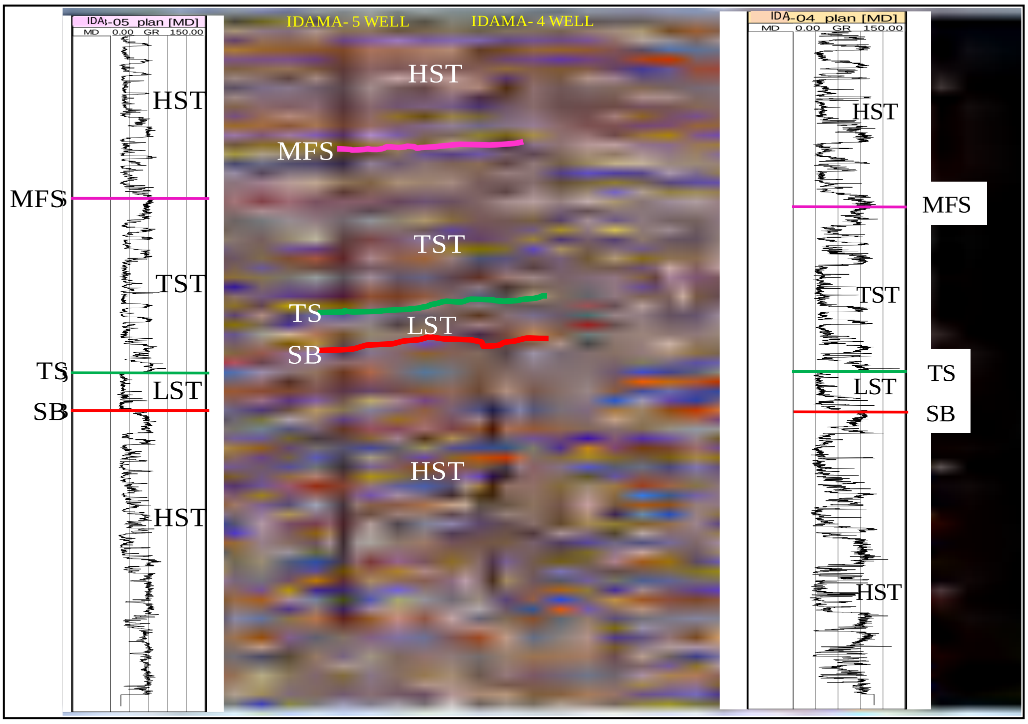

Figure 14: Stratigraphic Surfaces and Systems Tracts of Ida-4 and 5 wells and their correlation on the crossline of the seismic section.

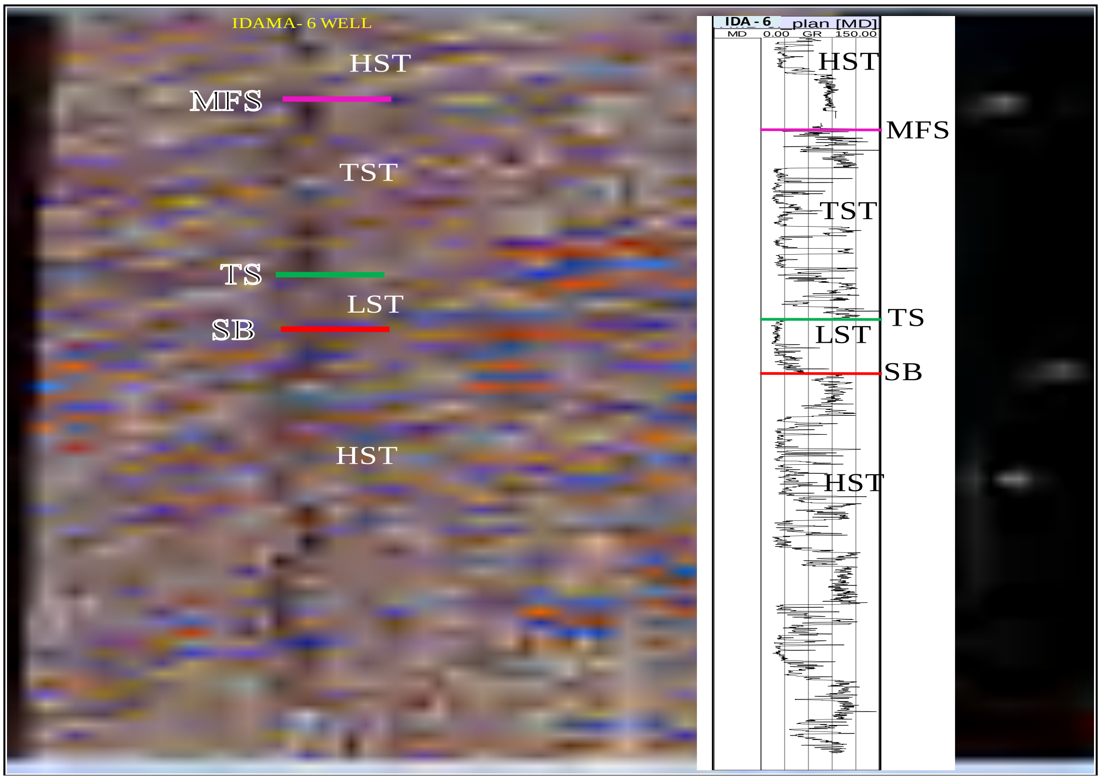

Figure 15: Stratigraphic Surfaces and Systems Tracts of Ida-6 well on the inline of the seismic section

Seismic to Well Log Correlation of the Ida-4, 5 and 6 Wells

Seismic to well tie operation was performed using Petrel software. Similar chronostratigraphic surfaces (MFS, TS and SB) and systems tracts (HST, TST and LST) have been identified in the studied wells. These stratigraphic surfaces and systems tracts delineated in Ida-4 and 5 wells located on the crossline were correlated to that of Ida-6 well located on the inline of seismic session (Figure 16). The Gamma Ray Log signatures of the wells aided the correlation on the seismic section. The correlation was done using the recognised chronostratigraphic surfaces. This correlation depicts lateral continuity and discontinuity of the genetically related stratigraphic units. It shows how the surfaces correlated along strike (crossline) and dip (inline) at certain

depths within the depositional basin, thus depicting basin geometry and depositional sequences across the three wells in the Ida field.
The displayed correlation indicates that the stratigraphic section appears to be dipping west and striking in the NE–SW direction. The occurrence of the identified chronostratigraphic surfaces at different depths along dip and strike lines in the studied wells indicates evidence of faulting and lateral variation of the stratigraphic units in the studied field.

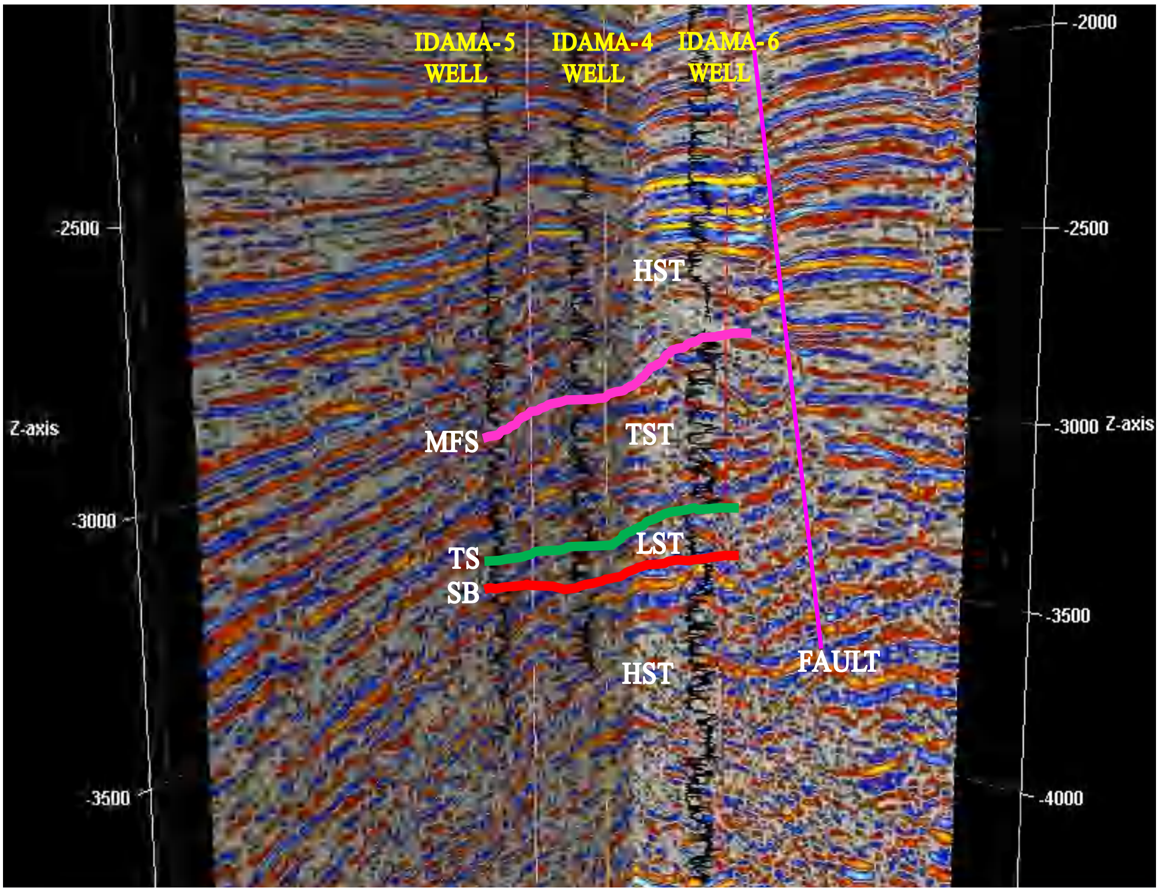

Figure 16: Log aided seismic correlation of Ida-4 and 5 wells on the crossline and Ida-6 well on the inline of the seismic section

CONCLUSION

The lithology, texture, age, shale sand ratio and wireline log data indicate that the entire interval studied in the Ida-4, 5 and 6 wells belong to the Agbada Formation (Whiteman 1982). The formation is made up of alternating sand and shale units which suggests rapid shoreline progradation. The sands are mostly sub-angular to sub-rounded, occasionally rounded and generally poorly to moderately well sorted. Ferruginous materials, shell fragments and carbonaceous detritus characterized the sequence while mica flakes, pyrites and glauconite pellets are rare and fairly regular. The Paralic Lithofacies Sequence has been subdivided further into an Upper and Lower Paralic unit. The regular sand and shale intercalation pattern on the Gamma Ray log permits easy recognition of sub-cycles (authocyles) of sedimentation in an extensively developed Paralic sequence. Rapid sedimentation rates which support organic matter preservation are inferred on the basis of the thick Paralic section. Paleoenvironmental reconstruction using index accessories recognized shallow water settings with intermittent deeper water conditions, supporting organic matter accumulation necessary for hydrocarbon formation. Sand bodies which represent sub-environments within these settings are deposited in mostly channel and bar deposits which have been recognized to be most common in deltaic settings, (Sneider et al. 1978). Depositions of the sediments of the analyzed intervals were interpreted as occurring during sub-cycles (authocyles) of sedimentation in lower delta plain, delta front and prodelta environments. The sandstone units within the HST and LST interpreted as channels deposits form good potential reservoirs within the Ida field. The shale units of HST and TST could serve as excellent top and bottom sealing rock for hydrocarbon in the reservoir. These shale units could equally serve as good source rocks. The shale units (seals) of TST and HST, and reservoir rocks of LST and HST combined to form the stratigraphic traps for hydrocarbon accumulation in the Ida field that could be targeted during hydrocarbon exploration. The Condensed Section together with the associated MFS serve as regional seals and source rocks in the field. The study showed good correlations of the lithology and Systems Tracts of the wells, though the penetrated stratigraphic intervals of Ida-4 and -5 appear far shallower than their equivalent settings in Ida-6 which is further up dip of the area. This could helpful in directing of well trajectory during horizontal drilling operation. The sandstone and shale units of the systems tracts are excellent hydrocarbon reservoirs targets and sealing rocks respectively. The lateral continuity of sandstone units (potential reservoirs) depicted in the lithofacies subcycles and systems tracts correlations is useful in the determination of reservoirs geometry, areal coverage and calculation of the volume of accumulated hydrocarbon.

REFERENCES

Adegoke O.S., 2002. High resolution biostratigraphy, sequence stratigraphy and 3-D modeling. Indispensable tools for E & P activities in the New Millenium, Nigerian Association of Petroleum Exploration, 16, 46 – 65.

Adeniran A.O., 2014. Lithostratigraphy, Palynostratigraphy and Palynofacies Indications of the Depositional Environments of Upper Cretaceous to Paleogene Sediments, Offshore Eastern Dahomey Basin, SW Nigeria Journal of Earth Science Research, 2, 118 – 128; DOI: 10.18005/JESR0204001

Adojoh, O., Lucas F. A., & Dada, S., 2015. Palynocycles, Palaeoecology and Systems Tracts Concepts: A Case Study from the Miocene Okan-1 Well, Niger Delta Basin, Nigeria. *Applied Ecology and Environmental Sciences*, 3, 66-74. doi: 10.12691/aees-3-3-1

Armentrout, J. M., 1991. Paleontological constraints on depositional modeling; examples of integration of biostratigraphy and seismic stratigraphy, Gulf of Mexico. In P. Weimer & M. H. Link (Eds.), *Seismic facies and sedimentary processes of submarine fans and turbidite systems* (pp. 100 – 170). Mexico: Springer-Verlag.

Bankole S.I., Schrank E. & Osterloff P.L., 2014. Palynostratigraphy, palaeoclimates and palaeodepositional environments of the Miocene aged Agbada Formation in the Niger Delta, Nigeria. Journal of African Earth Sciences, 95, 41 – 62.

Batten, D. J. & Stead, D. T., 2005. Palynofacies analysis and its stratigraphic application. In: E. A. M. Koutsoukos (Ed.), *Applied stratigraphy* (pp. 203-226). Netherland, Springer

Beka F.T. & Oti M.N., 1995. The Distal Offshore Niger Delta: Frontier Prospects of a Mature Petroleum Province. In: Oti M.N. & Postma G. (eds.), Geology of Deltas, Rotterdam A.A., Balkema press, 237 – 241.

Boggs S.Jr., 2006. Principles of stratigraphy and sedimentology. United States of America: Pearson Education Inc. p. 585.

Chukwuma-Orji, J. N., Okosun, E. A., Goro, I. A. & Waziri, S. H. 2017. Palynofacies, sedimentology and palaeoenvironment evidenced by studies on IDA-6 well, Niger Delta, Nigeria. *Paleoecology of Africa*, **34**, 87-105.

Chukwuma-Orji, J.N., Okosun E. A., Alkali, Y. B., Fadiya L. S. & Taiwo O.M. 2017. Palynofacies Analysis of Ida 5-well, Niger Delta Basin, Nigeria, Nigeria Journal of Engineering and Applied Sciences, vol. 4 (2), pp. 95 – 112.

Chukwuma-Orji J.N., Okosun E.A. & Gana F.D., 2019. Palynofacies analysis of Ida-4 well, Niger Delta Basin, Nigeria. Geology, Geophysics & Environment, 45, 219 – 230.

Doust H. & Omatsola E., 1990. Niger Delta divergent/passive margin basins, American Association of Petroleum Geologists Memoir, 48, 201 – 238.

Durugbo E.U. & Uzodimma E., 2013. Effects of lithology on palynomorph abundance in wells X1 and X2 from the Western Niger Delta, Nigeria. International Journal of Geology, Earth and Environmental Sciences, 3, 170 – 179.

Galloway W. E., 1989. Genetic stratigraphic sequences in basin analysis 1: Architecture and genesis of flooding-surface bounded depositional units. American Association of Petroleum Geologists Bulletin, 73, 125 – 142.

Hallsworth C. R. & Knox R. W. O'B., 1999. British Geological Survey rock classification scheme. Volume 3 classification of sediments and sedimentary rocks. British Geological Survey Research Report, 99-03.

Haq, B.U., Hardenbol, J. & P.R. Vail, P. R. (1988). Mesozoic and Cenozoic chronostratigraphy and cycles of sea level changes, *The Society of Economic Paleontologists and Mineralogists*, 42, 71-108.

Obaje, N. G., 2009. Geology and mineral resources of Nigeria. Springer Dordrecht Heidelberg London New York. Doi:10.1007/978-3-540-92685-6

Olayiwola, M. A. & Bamford, M. K., 2016. Petroleum of the Deep: Palynological proxies for palaeoenvironment of deep offshore upper Miocene-Pliocene sediments from Niger Delta, Nigeria Palaeontologia Africana, 50, 31–47.

Onyekuru S.O., Ibelegbu E.C., Iwuagwu J.C., Essien A.G. & Akaolisa C.Z., 2012. Sequence stratigraphic analysis of "XB Field", Central Swamp Depobelt, Niger Delta Basin, Southern Nigeria. International Journal of Geosciences, 3, 237 – 257. doi: org/10.4236/ijg.2012.31027.

Poumot, C., 1989. Palynological evidence for eustatic events in the tropical Neogene. *Bulletin Centres Recherche Exploration-Production d'Elf-Aquitaine* 13, 437- 453.

Reijers T.J.A., 2011. Stratigraphy and sedimentology of the Niger Delta, Geologos, 17, 133 – 162, doi:10.2478/v10118-011-0008.3

Reijers, T. J. A., Petters, S. W. & Nwajide, C. S., 1996. The Niger Delta basin, sedimentary geology and sequence stratigraphy. In T. J. A. Reijers (Ed.), *Selected chapters on geology* (pp. 100 - 117). Warri: SPDC Corporate Reprographic Services.

Selley R.C., 1978. Concept and methods of subsurface facies analysis, American Association of Petroleum Geologists Bulletin Education course notes, series no 9, 1 – 86.

Selley R.C., 1976. Subsurface environmental analysis of North Sea sediments, American Association of Petroleum Geologists Bulletin, 60, 184 – 195.

Short K.C. & Stauble A.J., 1967. Outline of the geology of Niger Delta, American Association of Petroleum Geologists Bulletin, 51, 761 – 779.

Sneider R.M., Tinker C.N. & Merkel L.D., 1978. Deltaic environment, reservoir types and their characteristics. Journal of Petroleum Technology, 1, 1538 – 1546.

Thomas, M. L., Pocknall, D. T., Warney, S., Bentley, S. J. Sr., Droxler, A. W. & Nittrouer, C. A., 2015. Assessing palaeobathymetry and sedimentation rates using palynomarceral analysis: a study of modern sediments from the Gulf of Papua, offshore Papua New Guinea. *Palynology*, 0, 1 – 24. doi: org/10.1080/01916122.2015.1014526

Tyson, R. V., 1993. Palynofacies analysis. In D. J. Jenkins (ed.). *Applied Micropalaeontology* (pp. 153-191). Dordrecht: Kluwer Academic Publishers.

Tyson, R. V. (1995). *Sedimentary Organic Matter: organic facies and palynofacies* (pp. 600 - 615). London: Chapman & Hall.

Vail P.R., 1987. Seismic stratigraphy interpretation, using sequence stratigraphy. Part I: Seismic stratigraphic procedure. In: Balley A.W. (ed.), Atlas of seismic stratigraphy 1, American Association of Petroleum Geologists, Tulsa, 1 – 10.

Vail, P. R. & Wornardt, W.W., 1991. An integrated approach to exploration and development in the 90s, well log-seismic sequence stratigraphic analysis. *Transactions - Gulf Coast Association of Geological Societies*, 41, 630 – 650.

Weber K.J., 1971. Sedimentological aspects of oil fields in the Niger Delta, Geologie en Mijnbouw, 50, 559-576.

Whiteman A.J., 1982. Nigeria its petroleum geology, resources, and potential vols. 1 and 2. Graham and Trotman, ltd., London, 176 – 238

©2023 This is an Open Access article distributed under the terms of the Creative Commons Attribution 4.0 International license viewed via https://creativecommons.org/licenses/by/4.0/ which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is cited appropriately.